THE ROLE OF WORKING MEMORY IN INTEGRATIVE READING OF TEXT AND PICTURE: AN EYE TRACKING STUDY

A Dissertation

by

SUNGYOON LEE

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Chair of Committee,	Kausalai (Kay) Wijekumar
Committee Members,	Emily Binks-Cantrell
	R. Malatesha Joshi
	Steven Woltering
Head of Department,	Michael A. de Miranda

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ABSTRACT

Despite beliefs about the effectiveness visualization has on learning, researchers have found that adding pictures to text does not always lead to better learning outcomes. Although extensive empirical research has examined the relevant factors that can enhance the effects of images added to text, individual differences in underlying cognitive capacities are relatively unexplored in the literature. As such, the purpose of this dissertation study is to examine the role of executive control in the integrative reading processes of elementary students as well as the learning outcomes of students who read illustrated scientific texts through the observation of their eye movement patterns.

To achieve this goal, this study examines three research areas: the first investigates the unique, direct contributions of fourth and fifth grade students' integrative reading of text and pictures as evidenced by eye movement patterns and the link to their learning outcomes, while controlling for contributions of working memory capacity. The second examines the unique, direct contributions of fourth and fifth grade students' working memory capacity to their comprehension of illustrated science texts. The final study examines unique, direct contributions of fourth and fifth grade students' working memory capacity to their reading processes, including text processing, picture processing, and the integrative reading of text and pictures.

This dissertation is expected to contribute to the extant theoretical and empirical literature. First, the results supplement current theories of multimedia learning by specifying the role of attention shifting and inhibitory control. In the current multimedia learning theories, the role of executive control is not clearly determined. Findings in this study further examine the current cognitive model of text-picture integration by recognizing the significant role of executive control capacity in learners. Second, the results will extend current knowledge about

elementary school students' cognitive processes when reading illustrated science texts through the use of an eye tracking technique. Finally, for the upper elementary students, who advance from the *learning to read* to *reading to learn* stage, identifying relevant cognitive factors in learning with visualizations will provide foundations for creating and delivering adequate interventions.

DEDICATION

To my son, Aiden and my wife, Donghyun.

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CHAPTER I

INTRODUCTION

The idea that learning is improved by adding images to text is long-standing, at least since John Comenius' *Orbis Sensualium Pictus* (Visible World in Pictures; 1658). Given the belief about how effective visual representations are for learning, there is a wide adoption of images in science textbooks. Researchers and educators have maintained the belief that there are particular benefits in using visual representations alongside text rather than using text alone. In some cases, visual representations might better represent the relation among different objects or procedures of scientific mechanisms (Cook, Carter, & Wiebe, 2008) than do textual representations on their own. Hence, visual representations not only attract the attention of learners and motivate students (Mayer, Bove, Bryman, Mars, & Tapangco, 1996), they also enhance knowledge retention (Peeck, 1993) and facilitate connections between new and existing knowledge (Roth, Bowen, & McGinn, 1999).

However, the effectiveness of visual representations is controversial; adding pictures to text does not always lead to better learning outcomes (Bartholomé & Bromme, 2009). Providing visual representations may actually increase the cognitive demand for learners (Mayer & Moreno, 1998; Paivio, 1986; Schroeder & Cenkci, 2018). When reading illustrated texts, readers need to effectively split their attention between text and images, then integrate verbal and nonverbal information in order to construct a coherent mental model. This additional cognitive demand might hamper learning by overloading the processing capacities of learners. Therefore, researchers (e.g., Baadte, Rasch, & Honstein, 2015; Höffler, 2010; Mayer, 2014; Scheiter & Eitel, 2015; Schnotz & Wagner, 2018) have identified various types of learner-related and text-related factors involved in the integrative comprehension of text and pictures in order to better examine for whom, when, and in what condition visual representations help learning.

To date, extensive research has examined the effects of text-related variables (e.g., labeling, highlighting, color coding, spatial and temporal contiguity) on students' integrative comprehension (see Jamet, 2014; Mason, Pluchino, & Tornatora, 2013; Scheiter & Eitel, 2015; see Richter, Scheiter, & Eitel, 2016 for a review). For instance, when there are visual cues or signals for corresponding elements in text and picture, learning outcomes generally improve (i.e., *signaling effect*). When text and visualizations are presented in a temporarily and/or spatially close manner, learning outcomes are also enhanced (i.e., *contiguity effect*) (Mayer, 2014). The studies on text-related factors have provided significant implications to the designs of textbooks and learning materials.

Multimedia benefits may not be just from explicit cues, but also from the nature of human information processing (Brunyé, Taylor, Rapp, and Spiro, 2006). However, the role of individual differences in the underlying cognitive processes in text-picture integration has been relatively unexplored (Renkl & Scheiter, 2017). Particularly, working memory as a domain-general factor has rarely been examined in literature regarding the learning of science with illustrated text. Thus, the present dissertation study was designed to examine the role of working memory in text-picture integration, specifically by focusing on attention shifting and inhibitory control as subcomponents of executive control. This research study used an eye tracking technique to observe the online reading behaviors of fourth and fifth grade elementary students while they read both illustrated and non-illustrated science texts. The findings and implications derived from this research will help delineate cognitive mechanisms underlying the learning of science with illustrated texts, and inform future design guidelines for textbooks and learning materials with visualizations.

Visual Literacy in Science Learning

Visual representations are used extensively for communicating information in newspapers, websites, and science textbooks (McTigue & Flowers, 2011). Students are frequently exposed to visual representations while reading science textbooks; the picture-to-text ratio in those science textbooks has increased in recent years (Cook, 2006; Jian, 2016). As the use of visual representations has become more prevalent, new language skills such as *viewing* and *representing* have been added to the curriculum, in addition to traditional language skills such as *reading, writing, listening,* and *speaking.* Learners' ability to understand multiple modes of representations (i.e., *representational competence*) has become an essential skill in today's learning of science (Tippett, 2016). Thus, Next Generation Science Standards (NGSS; Achieve, Inc, 2013) promote visual literacy as a fundamental ability to participate in informed discussion of science-related topics.

Using visual representations has a potential benefit for communicating scientific knowledge. Scientific knowledge is often composed of spatial relations among different objects. Due to the depictive nature of visual representations, learners can more efficiently acquire scientific concepts or ideas from visual adjuncts. For example, visual representations (i.e., a picture or a diagram) of a flower better represents knowledge about the structure of a flower. A series of pictures will better represent the phases of the moon than a mere textual description. Therefore, by using visual representations that correspond to textual information, learners are able to form deeper knowledge of particular scientific concepts, ideas, and principles.

Unfortunately, however, visual representations do not always bring educational benefits to scientific learning. The use of visual representations inevitably causes extra cognitive demands because learners need to process multiple representations. According to Renkl and Scheiter (2017), several challenges exist in learning with visual representations. First, learners might have internal biases, such as that text carries relevant information while pictures are ancillary or merely entertaining. Second, learners need to have a variety of knowledge and skills to comprehend visual representations, such as domain knowledge and spatial skills. Third, learners should focus on relevant information while not being distracted by perceptually salient information (Cromley et al., 2016). Finally, information from visual representations needs to be integrated with text. Adding visual representations into text yields all of these new challenges.

Despite the aforementioned challenges, the process of how to learn from and with visual representations is rarely taught explicitly in schools. Coleman, McTigue, and Smolkin (2011) found that elementary teachers' most common practice of teaching visual representations in science was *pointing to them*. This finding revealed that elementary school teachers often do not provide guidance for how to use or interpret visual representations, nor how to efficiently integrate the visual information with text segments in order to better understand any scientific concepts being taught.

Types of Visual Representations

There are various types of visual representations, including but not limited to: pictures, graphs, charts, diagrams, maps, and images. Therefore, it is important to clearly delimitate the concepts of visual representations the current study examines. Even though there is no standard typology of visual representations, several categorizations have been suggested. For example, Carney and Levin (2002) categorized visual representations into four types based on their functions: decorative, representational, organizational, and interpretational. According to this categorization, decorative pictures only aim for attracting or pleasing learners without having any significant relation with the content presented in the text. In contrast, representational pictures mirror part or all of what is described in the text. Organizational pictures show a structural framework for the text content. Finally, interpretational pictures help readers understand difficult text describing scientific or technical concepts.

Carney and Levin (2002) did not include the text genre in their categorization but, in a recent review, McCrudden and Rapp (2017) focused only on informational text, and categorized visual representations into semantic visual representation (e.g., graphic organizer) or pictorial visual representation (e.g., picture). The two types of visualizations differ in their conventions. While the semantic representations use symbols, the pictorial representations use images. This corresponds to the classifications of schematic and iconic diagrams by Hegarty, Carpenter, and Just (1996).

In the current study, which focuses on the comprehension of scientific texts, the focus was on the pictorial visual representation from McCrudden and Rapp's categorization (or interpretational representation from Carney and Levin, 2002). This is because a) integrative comprehension is not required for decorative visualizations where no corresponding information exists between text and pictures; and b) the current study is particularly interested in coherence formation between *rule-based* and *similarity-based information*. While pictorial representation is associated with their referent only by *similarity* (Schnotz, Wagner, Ullrich, Horz, & McElvany, 2017), the semantic representation relies on both *rule* and *similarity* (e.g., graphic organizer; for detailed distinction between rule-based and similarity-based information processing, see Hahn & Chater, 1998).

Additionally, in multimedia learning research, pictorial visualizations can have different forms: static visual representations or dynamic visual representations (e.g., animations; McCrudden & Rapp, 2017). With the recent advancement in computer technology and widespread access to the Internet, animations have become a popular instructional aid. With this trend, there has been a set of studies that examine the effects of animations (or dynamic visualizations) over the effects of static pictures. An emerging consensus is that animations are more effective than static pictures for those who have low spatial abilities (e.g., Höffler, 2010; Kühl, Stebner, Navratil, Fehringer, & Münzer, 2017). Despite the increasing use and benefit of animations or dynamic visualizations, the current study will restrict the scope to static visual representations because they are most likely encountered by students while reading science textbooks in current school curriculum.

Individual Differences in Learning with Visuals

A few studies have focused on individual differences in learning visualizations such as age, prior knowledge, reading comprehension skill, and working memory. Individual differences in those constructs need to be considered while examining learning with visualizations. because the effects of any types of textual or visual supports interact with the cognitive and linguistic conditions of learners. Specifically, these learner-related factors may either compensate (e.g., ability-as-compensator hypothesis) or enhance (e.g., ability-as-enhancer hypothesis) the effects of text-related supports. The investigation of the learner-related factors is important to determine for how and for whom those text-related factors are effective.

Previous research revealed that age or grade level is associated with integrative reading of text and picture. For example, Jian (2016) found that while reading an illustrated science text, fourth grade readers tend to focus on a single representation (i.e., either text or picture), whereas college readers attempt to integrate both representations. This finding suggest that the integrative reading behaviors might be a mature or a more educated reading behavior. Fourth grade students are not fully developed to be able to integrate both textual and pictorial information while reading illustrated text. However, it is essential to note a limitation Jian's study is that they do not specifically indicate the source of the difference between the younger and older learners. A number of variables are confounded with age difference including, but not limited to, cognitive capacity, prior knowledge, basic reading skills, maturity, and advanced reading strategy.

Prior knowledge is another factor that has been examined in learning with visualization research. Because integration of incoming information with existing knowledge is part of comprehension processes, both domain-general and domain-specific knowledge is, theoretically, necessary for comprehending text. A large body of text comprehension research found that prior knowledge has an impact on reading comprehension, specifically with inferential reading (Kendeou, Van Den Broek, 2007; Ozuru, Dempsey, & McNamara, 2009). Similarly, prior knowledge might also have an impact on both reading behavior and learning outcomes when reading illustrated text. When learners are more familiar with content, it is expected that they are more likely to display integrative reading behaviors. Consistent with this theoretical assumption, Mason, Pluchino, and Tornatora (2013) found that elementary students' prior knowledge about the topic is highly associated with their integrative comprehension of text and pictures.

Among different learner-related factors, the investigation of working memory is particularly important in learning with visualizations. This is because not only is the use of illustrated materials motivated by the nature of working memory, but it also demands learners' effective use of working memory resources (Wiley, Sanchez, & Jaeger, 2014). Specifically, while processing multiple representations, learners need to a) maintain the goal of the learning;

b) attend to available information; c) select the information relevant to the learning goal from what is available; d) organize the presented information in memory based on the learning goal; e) maintain the learning goal and representations of the incoming information in working memory; and f) retrieve necessary information from long-term memory in order to develop an integrated representation of the presented information (Lusk et al., 2009). Since attentional control is involved in processing multiple representations, “individual differences in working memory should theoretically be an important factor in multimedia learning” (Wiley et al., 2014, p.602).

Research Questions

The primary interest of the present study is to examine the relationships between working memory capacity, online reading behaviors, and reading comprehension outcomes. To achieve this purpose, the role of working memory is investigated in the integrative reading of text and picture and learning. Executive control, a subcomponent of working memory, is a particular interest to the present study. Baddeley’s working memory model and multimedia learning theories provided theoretical foundations of this study. Fourth and fifth grade elementary students’ integrative comprehension of science texts was observed by an eye tracking technique. More specifically, the current study was guided by the following three research questions:

1. Does fourth and fifth grade students’ integrative reading of text and picture, as evidenced by integrative eye movements, make unique and direct contributions to their learning outcomes while controlling for the contributions of working memory capacity?
2. Does fourth and fifth grade students’ working memory capacity make unique, direct contributions to comprehension outcomes of illustrated science texts while controlling for the contributions of reading comprehension?

3. Does fourth and fifth grade students' working memory capacity make unique and direct contributions to text processing, picture processing, and integrative reading of text and pictures?

Definition of Key Terms

Working Memory: Baddeley and Hitch (1974) introduced the multicomponent model of working memory. The theory proposed a model containing three components: the executive control, the phonological loop, and the visuospatial sketchpad. Executive control is responsible for supervising the integration of information and for coordinating "slave systems" that are responsible for short-term maintenance of information. One slave system, the phonological loop, stores phonological information (that is, the sound of language) and prevents its decay by continuously refreshing it in a rehearsal loop. The other slave system, the visuospatial sketchpad, stores visual and spatial information. This information can then be used, for example, to construct and manipulate visual images and to represent mental maps.

Multimedia: According to Mayer (2014), this term has different meanings at different levels. First, on the technological level, multimedia can refer to the use of multiple delivery media, such as computers and mobile devices. Second, on the presentation level, it means the use of different representations, such as texts and pictures. Finally, on the sensory modalities, it refers to the use of multiple sensory organs, such as the eyes and the ears. In this paper, the term multimedia will be used in reference to the second meaning, which is the use of multiple representations, particularly texts and pictures.

Multimedia Text: Along with the definition of the term multimedia, multimedia text is defined as text that uses multiple representations. In the current study, multimedia text refers to text along with static pictures. The following terms will be used interchangeably: multimedia text, illustrated text, text with picture, text with illustration, text with visualization, text with visual representation.

Text-Picture Integration: Text-picture integration refers to learners' integrative comprehension of text and picture while reading illustrated texts. In this study, integrative reading behavior is distinguished from learning outcomes, and is observed by integrative eye movement transitions between text and picture.

Organization of the Study

Chapter I of this study included visual literacy in science learning, types of visual representations, the purpose of the study, research questions, and definition of terms.

Chapter II presents the literature related to learning with visualizations, integrative reading of text and picture, eye tracking research. Previous empirical research about the relations among readers' cognitive capacities, online reading behaviors, and reading comprehension outcomes will be presented.

Chapter III presents the research design, population, context, sample, instrumentation, data collection, and data analyses.

Chapter IV reports the results of the data analysis and a summary.

Chapter V presents the findings in context, the limitations of the study, and the significance of the study.

CHAPTER II

REVIEW OF LITERATURE

In the introduction, I outlined the relevant factors in learning with visualizations and visual literacy. In the review of literature, I present literature relating to the theoretical framework for the study and literature relating to learning with visualizations, visual literacy and eye tracking research. I also synthesize the literature on text-picture integration and identify gaps in the current literature. The reviews including research design, population, measures, duration, conditions, and results of included studies are summarized in the Appendix A.

Review of Theoretical Framework

In the literature of learning science and cognitive psychology, learning with visualizations has been underpinned and motivated by multiple cognitive theories of learning: Cognitive Load Theory (CLT; Sweller, 1994; Sweller, Van Merrienboer, & Paas, 1998), Dual Coding Theory (DCT; Clark & Paivio, 1991; Paivio, 1991), Cognitive Theory of Multimedia Learning (CTML; Mayer, 2014), and Integrated Model of Text and Picture Comprehension (ITPC; Schnotz & Bannert, 2003). While Mayer's (2014) CTML has been the most prominent theoretical foundation for learning with visualization research, studies have cited one or more theories with different emphasis. Also, Baddeley's working memory model has been adopted by different theories to explain how the brain processes multimedia. In this section, the working memory model is first reviewed and then other multimedia learning theories will be presented.

Baddeley's Working Memory Model

Working memory is the ability to process and temporarily hold information. Although there is an ongoing debate about whether working memory is a unitary or nonunitary concept (see Schweppe & Rummer, 2014), there has been a general consensus that working memory is composed of multiple subsystems, such as that of the phonological loop, the visuospatial sketchpad, and executive control (Baddeley & Hitch, 1974). In this tripartite framework, while the phonological loop concerns auditory and speech-based information, and the visuospatial sketchpad maintains and manipulates visual and spatial information, executive control is an attentional control system, operating in conjunction with the phonological loop and the visuospatial sketchpad. (Baddeley, 1998). Recently, Baddeley made a revision to add the episodic buffer, which stores multimodal information and combines information from the phonological loop and the visuo-spatial sketchpad with prior knowledge (Schüler, Scheiter, & Van Genuchten, 2011).

After Baddeley's multicomponent working memory model was suggested, studies (e.g., Bishop, North, & Donlan, 1996; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Smyth & Pendleton, 1990) have found behavioral evidence that the three subsystems (i.e., phonological loop, visuospatial sketchpad, and executive control) independently process information with their own limited capacities. Moreover, neuropsychological studies (e.g., Gathercole, 1994; Salmon et al., 1996) revealed that each of the subsystems is associated with the activities of different brain regions. Those research studies confirmed the differential role of working memory subcomponents. According to the studies, the phonological loop is the subsystem that processes verbal information, such as spoken and written words. Here, written words need to be converted from visual code into an articulatory code to be transferred to the phonological store, though spoken words directly enter the phonological loop (Schüler et al., 2011). The visuospatial sketchpad is the subsystem that processes both visual and spatial information. The visual component of the visuospatial sketchpad deals with visual characteristics of objects such as shape or color, whereas the spatial component deals with relational or spatial information.

Researchers (Baddeley, 1996; Miyake et al., 2000; Miyake & Friedman, 2012; Schnitzspahn, Stahl, Zeintl, & Kaller, 2013; van der Ven, Kroesbergen, Boom, & Leseman, 2013) have identified three major processes of the executive control system: attention shifting, inhibitory control, and updating. Specifically, attention shifting refers to the flexible allocation of attention between tasks and different stimuli; inhibition is the suppression of irrelevant information; and updating is the substitution of irrelevant information with relevant information in working memory.

From the multicomponent working memory model, the differential roles of working memory components can be generally assumed in learning with visualizations. To put it simply, it is likely that the phonological loop is responsible for text processing, the visuospatial sketchpad is in charge of image processing, and executive control exerts splitting attention, allocating memory resources, and integrating information from text and images. As summarized in the following section, different multimedia learning theories widely adopt Baddeley's multicomponent working memory model and its assumption about human cognitive structure.

Cognitive Load Theory

According to Sweller, Merrienboer, and Paas (1998), a key aspect of human cognitive structure is the limited nature of working memory capacity. To be stored in long-term memory, external information needs to be processed and temporarily held in working memory. Therefore, the limited nature of working memory capacity needs to be considered when designing instructional materials.

According to the CLT, learning materials produce three different types of cognitive demands on working memory capacity: intrinsic, extraneous, and germane. The intrinsic cognitive load is generated by the element interactivity determined by the number of elements that must be processed simultaneously. If the learning content is complex when compared to learners’ prior knowledge and generates interactions among the learning content, the intrinsic load increases. The extraneous cognitive load is caused by the ways in which information is presented. When learners are encouraged to engage in conscious cognitive processing that is directly relevant to the construction of schemata and the integration with prior knowledge, the germane cognitive load increases. Because the intrinsic cognitive load is inherent in the content itself, it cannot be altered. Instructional designers should try to alter both/either the extraneous and/or germane cognitive load to improve learning. The effects of learning with visualizations can be explained by CLT. Learning with visualizations can be viewed as reducing extraneous load and redirect learners’ attention to schema construction if the information presented is germane and users are adept at switching between the text and images.

Dual Coding Theory

Dual coding theory postulates that the human information processing system contains an auditory/verbal channel and a visual/pictorial channel (Paivio, 1971). With these two channels, information is processed in two distinct mental representations: verbal (i.e., spoken or printed words) and imaginal (i.e., pictures or animation). In these two processing systems, verbal and imaginal representations make an associative network that supports maintaining and retrieving information (Clark & Paivio, 1991). Later, Mayer and Sims (1994) adapted and modified dual coding theory to explain multimedia learning. From multiple experimental studies, Mayer and Sims concluded that concurrent presentation of verbal and visual descriptions increases the likelihood that students build connections between verbal and visual mental representations than successive presentation of the representations. If students could simultaneously utilize both the verbal and nonverbal routes to process and restore information, knowledge can be more easily activated from the long-term memory, thereby reducing cognitive load. Further, Moreno and Mayer (1999) examined whether narration with animation is more effective than on-screen text with animation. The authors found that using mixed-modality (i.e., narration with animation) has superior effects on both short-term memory and learning. To sum up, both Mayer and Sims (1994) and Moreno and Mayer (1999) not only suggest independent auditory/verbal and visual/pictorial processors in working memory but also evidence using multiple representations or modalities may have additive benefits for learning.

Cognitive Theory of Multimedia Learning

Even though CTML has been the most influential and frequently cited cognitive theory in multimedia learning research, the theory explicitly accepted the two-channel assumption suggested in DCT and the limited capacity assumption suggested in CLT. The flow of information processing in CTML is depicted in Figure 1. According to Mayer (2014), when learners read an illustrated text where textual and pictorial information are simultaneously presented, three main cognitive processes are executed in working memory: selection, organization, and integration. First, learners need to select information from verbal and nonverbal external representations. Second, learners need to organize the selected information, so they can establish coherent internal representations of the text and the illustration. Lastly, learners need to integrate the two internal representations by creating connections between them. Additionally, in each of the three processes, learners' prior knowledge is also involved in order to generate or activate internal concepts. As a result, a mental model of external content is constructed, integrated with prior knowledge in long-term memory, and the learning goal is achieved.

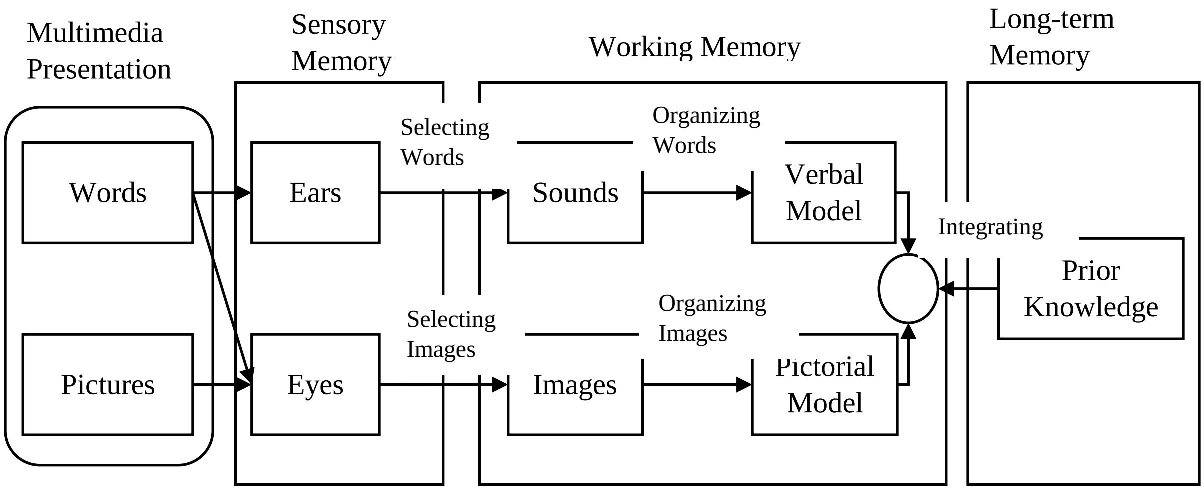

Figure 1. Mayer's Cognitive Theory of Multimedia Learning (reprinted from Mayer, 2014)

Integrated Model of Text and Picture Comprehension

ITPC also provides a theoretical description of the multimedia learning process. Even though it is similar to the description of CTML, there are some important differences. First, ITPC more focuses on the characteristics of textual and pictorial representations. Written texts are descriptive representations consisting of symbols, whereas pictures or visualizations are depictive representations consisting of iconic signs. Symbols in written texts are arbitrary because no relation can be found between the text symbols and the meanings the symbols deliver. The relation is only determined by a convention. In contrast, iconic signs are based on the similarity to the object to which the icons refer. For example, in a picture of a train, the picture needs to have a similar look with the object (i.e., train) to which the picture is referring.

Another difference of ITPC from CTML is that ITPC distinguishes sub-semantic and semantic processing. As shown in Figure 2, while reading a multimedia text, readers produce a text surface representation from the text and generate a propositional representation, which is finally integrated with a mental model. On the other hand, while processing a picture, learners first construct a visual perception representation, then generate a mental model. The propositional representations and mental models interact continuously via processes of mental model construction and model inspection guided by cognitive schema. Even though the descriptive and depictive information is processed separately in this process, they interact each other to generate a mental model.

Lastly, another important distinction between CTML and ITPC is that, in CTML, text processing and picture processing are parallel while generating two separate mental models (i.e., verbal model and pictorial model) that will be integrated later, but in ITPC, the processes are asymmetrical. In the processes, not only is one mental model created (i.e., only one mental model is created; Schnotz & Bannert, 2003), but also the verbal and visual processing is qualitatively different in responding to the characteristics of verbal and visual external representations.

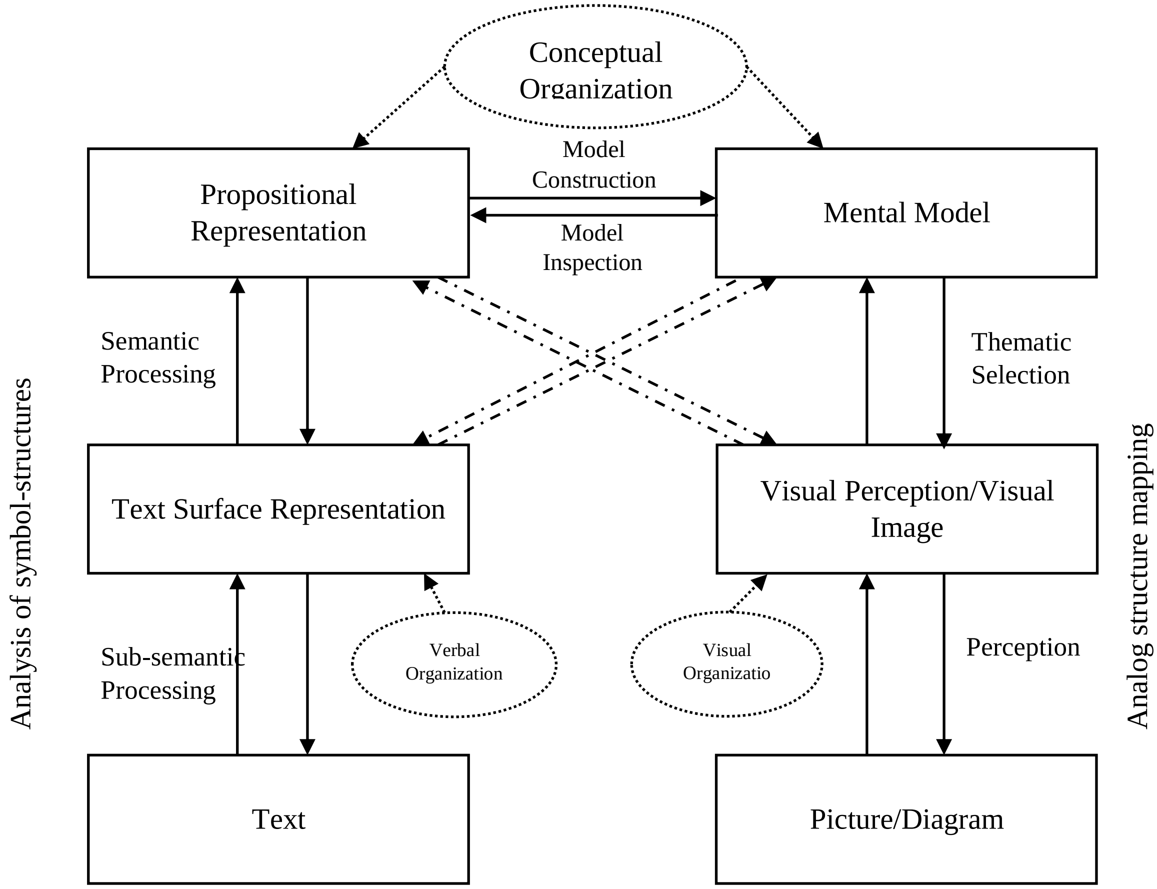

Figure 2. Integrated Model of Text and Picture Comprehension (reprinted from Schnotz & Bannert, 2003)

In conclusion, despite different emphases and foci, multimedia learning theories largely rely on Baddeley's multicomponent working memory model. In each theory, the roles of verbal and visuospatial working memory are rather clearly suggested or assumed: verbal working memory processes verbal representations and visuospatial working memory processes visual representations. However, in the multimedia learning models, the role of the executive control was not clearly specified and even tended to be overlooked in learning with visualization research. Therefore, an investigation of the role of executive control is essential for a thorough understanding of the underlying cognitive mechanisms in learning with visualizations (Brunyé et al., 2006).

In the following section, empirical research studies about the roles of different working memory components are reviewed. First, research studies regarding the role of working memory components in reading comprehension are discussed. Then, research about their effects on the learning with visualizations follows.

Role of Working Memory in Reading Comprehension

In reading comprehension research, it is well established that both verbal and visuospatial working memory components are essential cognitive resources when processing verbal texts. For example, Oakhill, Cain, and Bryant (2003) and Cain, Oakhill, and Bryant (2004) found a strong relationship between children's verbal working memories and their reading comprehension skills. Researchers (e.g., De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005; Gyselinck, Meneghetti, De Beni, & Pazzaglia, 2009; Meneghetti, Gyselinck, Pazzaglia, & De Beni, 2009; Pazzaglia, 1999) have also found that visuospatial working memory is involved in text processing, particularly when the text includes spatial information. This series of studies has confirmed that verbal working memory capacity is clearly associated with text reading, but the involvement of visuospatial working memory can vary according to the degree of spatial information in the text. Furthermore, Friedman and Miyake (2000) found that causal dimension and spatial dimension in text are independently processed in verbal and visuospatial working memory components.

The association between executive control and academic outcomes has been well identified (e.g., Christopher et al., 2012; Kieffer, Vukovic, & Berry, 2013). In reading comprehension research, studies have also suggested that executive control plays a significant role in text processing. For example, a meta-analysis conducted by Follmer (2018) found a moderate, positive association (r = .36) between executive control and reading comprehension. In this meta-analysis study, even though age, measure type, and publication type revealed no moderation effects, the type of executive control (i.e., attention shifting, inhibitory control, updating, and planning) moderated the association between executive control and text comprehension, and showed that attention shifting has a stronger association than the others. The author concluded that executive control has a significant effect on how one reads texts by allowing readers to integrate incoming ideas with previously-read texts while suppressing irrelevant information, and integrate new ideas with existing prior knowledge.

Empirical evidence on executive control was also provided with path analyses in Kieffer et al. (2013). In this study, the authors examined the association of attention shifting and inhibitory control with reading comprehension in fourth grade students. They found that both components of executive control make unique contributions to reading comprehension above and beyond the ability of students' word reading and language comprehension (attention shifting: z = 2.24, p < .05; inhibitory control: z = 2.62, p < .01). Based on their findings, the authors suggested that, in text comprehension, attention shifting facilitates higher order reading skills (e.g., re-reading, skimming, and searching for particular information), and may support flexible use of various reading strategies. Also, inhibitory control helps readers to suppress irrelevant information and inappropriate inferences.

Role of Working Memory in Learning with Visualizations

As the aforementioned multimedia learning theories suggest, verbal and visuospatial working memory components are expected to play a significant role in text-picture integration. This is because information needs to be temporarily stored and processed in working memory before it is stored in long-term memory (Schüler, 2017). For the last few decades, studies have increasingly examined the role of verbal and visuospatial working memory during reading texts that incorporate visual representations.

Studies have investigated the effects of visuospatial working memory when reading illustrated text. For example, a meta-analysis study (Höffler, 2010) found a positive relationship between spatial abilities and learning outcomes of texts with static pictures. The medium effect size of 0.34 indicated that learners who have high spatial ability benefit more when working with illustrated texts than those who have low spatial ability. This finding confirms the ability-as-enhancer hypothesis of spatial ability (see Huk, 2006; Mayer & Sims, 1994). A recent empirical study conducted by Kühl et al. (2017) also found that spatial ability acts as an enhancer when learning with static visual representations. The results of the study showed that low-spatial-ability learners struggled to mentally animate the static picture in order to construct an elaborate mental model. To appropriately process visual information, learners need to discern different shapes and colors, animate relative movements of the elements, and keep track of location changes.

Although the effect of verbal working memory on illustrated text comprehension has rarely been examined, verbal working memory is likely to play a role in comprehension of illustrated texts because text plays a significant part in illustrated learning materials. Recently, Schnotz et al. (2017) examined differential effects of verbal and spatial working memory in multimedia learning. In the study, 375 fifth-, sixth-, and seventh-grade students read both pure text and text with visual representations. The study confirmed that visuospatial working memory plays a greater role in comprehending text alongside visual representations than text without visual representations (z = 4.767, p < .001 for grade 5; z = 1.677, p < .047 for grade 6; z = 3.127,

p = .001). In contrast, they found that the effects of verbal working memory are the same for both the illustrated text reading and the pure text reading.

To summarize, verbal and visuospatial working memory components have differential roles when a reader is comprehending multimedia learning materials. The studies examining the roles of working memory components in learning outcomes provide significant implications on comprehending text with visual representations. However, there is a limitation that needs to be addressed. It is uncertain whether the better learning outcomes of students with high verbal and visuospatial working memory are actually derived from their integrative reading of text and pictures. It is plausible that students who have high verbal and visuospatial working memory capacities can effectively learn science concepts and ideas without integrating visual representations when reading. In this case, integrative reading of text and picture may not necessarily be connected with their learning outcomes. Thus, when considering learning outcomes, it is important to look at the online reading behaviors of readers in addition to examining working memory. Even though one potential approach to gathering online reading behaviors is eye-movement tracking, other indirect measures have been used in the literature. The following section will review those indirect measures first.

Online Reading Behaviors in Learning with Visualizations

In multimedia learning research, two approaches have been used to indirectly examine the reading process of readers, especially the integrative reading of text and pictures: the integrated item approach and the secondary task approach. Using the integrated item approach, Baadte et al. (2015) examined the effect of executive resources on university students' integrative comprehension of texts and pictures. They used computerized attention switching tasks and reading span tasks to assess students' capacity of executive control. Reading comprehension outcomes were evaluated by using both one-source and two-source items. One-source items are items that can be answered by extracting and processing information from either text or pictures, whereas two-source items require learners to process both text and pictures, then integrate the textual and pictorial information. Thus, scores on the two-source items indicate learners' performance of integrative reading of text and picture. The findings in the study suggest that students with lower switching capacities have difficulties allocating their attention to the text and the corresponding elements of the pictures, resulting in difficulties integrating information. Similarly, Schnotz et al. (2017) assessed the ability of fifth, sixth, and seventh grade students to dually process verbal and pictorial information when integrating text and images. The study found that both verbal and spatial working memory components contribute to the readers' integrative reading of text and pictures.

Another indirect way of examining reading processes is to use secondary tasks. In this approach, students are given a secondary task in addition to a primary task. If both primary and secondary tasks rely on the same subcomponent of working memory, their performance on the primary task will decrease (Schüler et al., 2011). In a study conducted by Brunyé et al. (2006), undergraduate participants were divided into different secondary task groups: a control group, a verbal group, a visuo-spatial group, and an executive control group. Participants then read three different formats of assembly instructions which were either text-only, picture-only, or a multimedia version. The authors found that verbal secondary tasks selectively interfered with phonological resources, which resulted in the decrease in performance with the text-only version, but not with the picture-only and multimedia versions. In contrast, visuo-spatial secondary tasks selectively interfered with visuo-spatial resources, impairing the performance in the picture-only or multimedia formats. Furthermore, executive control secondary tasks exclusively interfered with multimedia text processing. These findings about the roles of different working memory components are consistent with suggestions from multimedia learning theories as well as Baddeley's multicomponent working memory model.

Schüler et al. (2011) reviewed and synthesized those studies using either the integrated-item approach or the secondary-task approach. Although only a few relevant studies were identified, the hypotheses regarding differential roles and the unique contributions of different working memory components to text-picture integration were confirmed. The authors concluded that verbal information is processed in verbal working memory, pictorial information is processed in visuospatial working memory, and connecting/integrating information is implemented in executive control.

The integrated item approach and secondary task approach provide valuable information on the roles of working memory components in learning with visualizations. However, a couple of limitations need to be mentioned. First, for the integrated item approach, psychometric properties of the integrated item test need to be examined. Second, for the secondary task approach, it is difficult to maintain the material equivalence, or independence, among different versions of stimuli. For example, in Brunyé et al. (2006), students encountered the same content in the three different formats (text-only, picture-only, and multimedia). This design may threaten students' performance on the reading tasks.

More importantly, neither approach directly captures how readers process integrative reading. An emerging research technique that can be used to directly observe reading processes is an eye tracking technology. Direct observation with the eye tracking technique will provide more accurate information about readers' reading processes with illustrated materials. The following sections describe the current use of eye tracking in reading and learning with visualization research.

Eye Tracking Technique in Reading Research

Eye tracking technology has been extensively used in reading research for decades (Rayner, 2009). Eye tracking research is grounded in the eye-mind hypothesis (Just & Carpenter, 1980) which assumes that visual information that is currently being observed reflects underlying cognitive processes. In other words, where one is looking is what one is thinking about. Based on this hypothesis, eye tracking research in reading has presented various eye movement patterns, which are believed to reflect different reading processes from low level word recognition and lexical access to higher level integration and problem solving (Rayner, 1998). Providing extensive moment-to-moment data, eye movement patterns might capture reading processes more precisely than traditional reading tasks or measures (Rayner, 1998). Readers' eye movements offer extremely accurate and fine-grained information of the reading processes (Schroeder, Hyönä, & Liversedge, 2015).

Despite the extensive use of eye tracking technology in reading research, the examination of elementary students' gaze behaviors has been limited (Schroeder et al., 2015). One major reason cited for this has been technical difficulties such as low calibration rates and low-quality of recording. Recent advances in eye tracking systems, including increased precision, have allowed more research to examine children's reading behavior by providing more accurate data. Nevertheless, as Schroeder et al. pointed out studies with populations other than college-age participants are still limited. Therefore, the present research focuses on elementary school-aged readers to examine their eye movement patterns while reading illustrated science texts.

Eye Movement Indicators for Text-Picture Integration

The eye tracking technique is being increasingly adopted by learning with visualization research because it captures learners' cognitive processes more precisely while they integrate information from text and pictures. In eye tracking research, basic eye movement behaviors are known as fixations, saccades, and regression. While fixations refer to maintaining one's gaze on a certain location, saccades indicate the movements between fixations. Regression refers to the movements back to text that has previously been read. Based on these basic eye movement behaviors, different eye movement indicators are calculated and are used to examine integrative reading processes in various types of multimedia texts.

Table 1 shows the eye movement indices used in text-picture integration research. A widely-used eye movement indicator for integrative reading is the *integrative transition* between text and picture, which is usually obtained by taking the sum of all saccadic movements from text to picture and vice versa. In literature, this parameter has been used in different research contexts with participants from various educational levels. For example, while examining fourth grade students' text-picture integration, Jian (2016) used the number of saccades between text and illustration. Meanwhile, Scheiter and Eitel (2015) used the same parameter to examine whether signals guide university students' integrative reading behaviors (i.e., *signaling effect*). A recent study conducted by Kühl et al. (2018) also used this parameter when examining static picture and animation.

Table 1
Eye Movement Indices in Text-Picture Integration Research

Name	Description or Calculation	Cognitive Processes
Integrative transitions	Total number of times the eye fixation is moved from the text to the picture and vice versa	Attempts to integrate text and picture
Corresponding transitions	Total number of times the eye fixation is moved from a text segment to the corresponding element of the picture and vice versa	Success of integration of text and picture
Look-from text to picture fixation time	Total duration of all regressive fixations on the picture while re-reading a text segment	Integration of text and picture
Look-from picture to text fixation time	Total duration of all regressive fixations on the text while re-inspecting the picture	Integration of text and picture

Even though the integrative transition generally shows readers' attempts to integrate text and picture, a more precise index was employed by Johnson and Mayer (2012) to capture the success or failure of the integrative transition. The authors used *corresponding transitions* (i.e., the number of times the learner moves eye fixation from the text to the corresponding part of the diagram) to observe whether learners' saccadic movements are actually directed from text to corresponding elements of pictures or vice versa. The authors also used the proportion of corresponding transitions (i.e., the number of corresponding transitions divided by the total number of text-to-picture transitions) to figure out the proportion of the successful integrations.

Researchers (e.g., Mason, Pluchino, & Tornatora, 2013; Mason, Tornatora, & Pluchino, 2013; Schüler, 2017) have adapted more advanced eye movement parameters that have been used in text comprehension research. In those studies, eye movement patterns are divided into first-pass and second-pass reading. While the first-pass reading reflects the first encounter with an area of interest (AOI) before the eyes move away from, the second-pass reading indicates the second time reading of the AOI. While focusing on the second-pass reading, Mason and colleagues (2013) and Schüler (2017) used two more finely grained eye tracking indices: *look-from text to picture* and *look-from picture to text.* The former is the total time of all regressive fixations on the picture while re-reading a text segment, and the latter is the total time of all regressive fixations on the text while re-inspecting the picture. The authors argued that while integrative transitions (i.e., the number of saccades between text and picture) only indicate the attempts to integrate text and picture, the look-from fixation indices show "how long the attentional focus remains on the picture after a gaze shift from the text, or the attentional focus is on the text after a gaze shift from the picture" (Mason, Tornatora, & Pluchino., 2013, P. 97). The study assumed that these "look-from" indices more precisely capture integrative comprehension because second-pass reading usually reflects more intentional and strategic reading processes.

CHAPTER III

THE PRESENT STUDY

Statement of the Problem

The comprehensive literature review revealed several research gaps in the field of text-picture integration research. First, the differential roles of working memory components (i.e., verbal working memory, visuospatial working memory, and executive control) were not confirmed. Even though previous studies have examined the roles of verbal and visuospatial working memory in learning with visualizations, the executive control has rarely been investigated. Therefore, it is important to examine the role of executive control when looking at integrative reading of text and picture and its effect on learning outcomes. The results of the current study will shed light on who would most benefit from visual representations and will also show the contexts in which the provision of visual representations can be most effective.

Second, in previous research, direct observation of elementary students' reading process was scarce. Instead, reading processes were indirectly assessed using integrative items or secondary tasks. Those methods may have limitations when attempting to precisely capture the cognitive processes of readers that are most relevant to learning with visualizations. The present study uses eye tacking technology to collect moment-to-moment eye movement behavior data. This data will provide extensive information about learners' cognitive processes while reading illustrated science texts. Finally, the relationship among executive control, online reading behaviors, and learning outcomes were not specified. Even though studies have investigated the effects of different working memory components on either reading processes or learning outcomes, few studies comprehensively examined the relationship among those variables. It is important to examine to what extent integrative reading facilitates learning, to what extent learning outcomes are derived directly from working memory resources, and to what extent working memory resources predict integrative reading behaviors.

To resolve the aforementioned limitations, the current study a) examines the effects individual differences in working memory capacity have on processing reading and learning outcomes when reading illustrated science texts, b) uses the eye tracking technique to more precisely observe elementary students' reading processes, and c) investigates the relationships among executive control, eye movement behaviors, and learning outcomes.

Purpose of the Study

This dissertation study aimed to examine the relationships between working memory capacity, online reading behaviors, and reading comprehension outcomes in fourth and fifth grade elementary students while they read illustrated scientific texts. While examining the relationships, the differential roles of working memory components were explored. Specifically, the study was guided by three research questions.

Research Questions

1. Does fourth and fifth grade students' integrative reading of text and picture, as evidenced by integrative eye movements, make unique and direct contributions to their learning outcomes while controlling for the contributions of working memory capacity?
2. Does fourth and fifth grade students' working memory capacity make unique, direct contributions to comprehension outcomes of illustrated science texts while controlling for the contributions of reading comprehension?
3. Does fourth and fifth grade students' working memory capacity make unique and direct contributions to text processing, picture processing, and integrative reading of text and pictures?

Participants

Recruitment flyers were sent out to the students and employees of Texas A&M University via the university's bulk-mail system. Parents who wanted their child to participate applied by filling out a Google form. The researcher then contacted the parents and scheduled lab visit dates and times. To be included in the sample, the participants needed to be fluent in English. Children who had severe developmental disorders (e.g., Autism Spectrum Disorders) and/or did not have normal or corrected-to-normal vision were excluded. The normal or corrected-to-normal binocular vision (20/40 or better) was confirmed by their performance on a standard Snellen chart. The study was approved by the Institutional Review Board (IRB2017-0007D). Twenty-eight fourth and fifth grade elementary students (mean age = 10.4; SD = 7.2; range: 8.92 ~ 11.08) were recruited during the Winter of 2018. Student demographics are presented in Table 2.

Table 2
Descriptive Statistics of Participants

	n	%
Total	28	
4^{th} grade	11	39.3
5^{th} grade	17	60.7
Female	12	42.9
Race/Ethnicity		
African American	0	0
Caucasian	15	53.6
Hispanic	4	14.3
Asian	6	21.4
Two or more races	2	7.1
Not report	1	3.6
Household income		
~ 50,000	5	21.4
~ 80,000	8	28.6
~ 100,000	2	7.2
More than 100,000	11	39.3
Not report	1	3.6

Measures

Description of the measures used to assess working memory, executive control, and reading comprehension is summarized in Table 3.

Table 3
Description of the Measures Used to Assess Working Memory, Executive Control, Reading Comprehension, Prior Knowledge, and Learning Outcome

Variable	Description of Task / Name of Test	Reliability
Working memory		
Verbal working memory	Digit span forward/backward subset; WISC	.83
Visuospatial working memory	Visual memory/sequential memory subset; VPST-4	.72; .81
Executive control		
Attention shifting	WCST-64	.76
Inhibitory control	Computerized color Stroop task	
Reading comprehension skill	WRMT-III	.88; .87; .90
Prior knowledge	Four open-ended questions for each reading topic	-
Learning outcome	Nine multiple choice and one open-ended questions	-

Note: WISC = Wechsler Intelligence Scale for Children; VPST-4 = Visual Perception Skill Test – 4; WCST-64 = 64 Card Version Wisconsin Card Sorting Test; WRMT-III = Woodcock Reading Mastery Test – III

Demographic Variables

The students' age, grade, gender, race/ethnicity, language used at home, special education indicator, household income level, parents' employment status, and parents' education level were collected.

Attention Shifting

Attention shifting was measured by the 64-card version of Wisconsin Card Sorting Test (WCST-64; Kongs, Thompson, Iverson, & Heaton, 2000). In the task, students were given cards that display different shapes with differing numbers and colors. They had to sort the cards along an unspecified criterion (e.g., color). Students were not told the sorting rule but were provided with feedback as to whether a given move was correct or incorrect. After 10 correct sorting moves, the sorting rule changed, and students were given feedback consistent with a new sorting rule (e.g., shape). The number of perseverative errors (i.e., errors in which students apply a previous rule after receiving feedback) was used as an indicator of difficulty with attention shifting (see Kieffer et al., 2013). The publisher reports adequate reliability for the perseverative error scores (generalizability coefficient = .76).

Inhibitory Control

A computerized color Stroop task using ePrime software was used to measure students' inhibitory control. In the task, students read two different conditions of color names: congruent condition and incongruent condition. In congruent condition, the color names and the color used for writing the color name were consistent (e.g., RED written in red). However, in incongruent condition, the color names and the color used for writing the color name were inconsistent (e.g., RED written in green). Each condition included 30 stimuli. Students' response time and accuracy were automatically recorded in ePrime software. The sums of response time of accurate answers were calculated. The difference of the response time between congruent and incongruent conditions were used for indicating students' capacity of inhibitory control.

Verbal Working Memory

Verbal working memory was assessed by digit span tests from Wechsler Intelligence Scale for Children (WISC). The task consisted of forward and backward digit spans. Students were told to repeat the digits presented by the experimenter both forward and backward. The series of numbers began with three-digit numbers and increased to eight-digit numbers. In the first round, children were instructed to repeat the digits in the same order as presented. In the second round, children were instructed to repeat the digits in reverse order. The test-retest reliability of the digit span task was reported as .83 (Alloway, Gathercole, Kirkwood, and Elliott, 2008).

Visuospatial Working Memory

Visuospatial working memory was measured by visual memory and sequential memory subtests of Visual Perception Skill Test (VPST-4). In the visual memory test, students were presented with a target image for five seconds and were asked to remember it. Then, they were instructed to find the target image from a collection of four different images, including the target image, on another page. In the sequential memory test, students were presented with a sequence of multiple images and were asked to remember the sequence. Then, they needed to find the same sequence of the images out of five different sequences of images. Internal consistency reliabilities were reported as .70 for visual memory and .81 for sequential memory. Test-retest reliability coefficients were reported as .72 for visual memory and .81 for sequential memory. Exploratory factor analysis reveals that the factor loadings for visual memory and sequential memory was .65 and .75 respectively, indicating these two subtests loaded onto a single factor (TVPS-4, Martin, 2017).

Reading Comprehension Skill

Reading comprehension skill was assessed by the passage comprehension subtest of the Woodcock Reading Mastery Test – III (WRMT-III; Woodcock, 2011). This widely used measure employs a cloze task where children were asked to read short sentences and identify missing keywords for blanks in order to accurately complete the sentences. The split-half reliability for fourth and fifth grade students was reported as .88 and .87, and test-retest reliability was reported as .90 (Woodcock, 2011).

Prior Knowledge

Four open-ended questions were used to assess students' familiarity of the topics and their prior knowledge. Table 4 shows the question items used for each reading topic.

Table 4
Prior Knowledge Items

Topics	Prior knowledge items
Steam train	1. Have you ever seen a steam train? 2. What do you know about a steam train? 3. Do you know how a steam train moves? 4. Do you know what is necessary for a steam train to move?
Airplane	1. Have you ever traveled by an airplane? 2. What do you know about an airplane? 3. Do you how an airplane takes off? 4. Do you know what is necessary for an airplane to take off?

Learning Outcome

Nine multiple-choice questions and one open-ended question were developed for each topic to assess students' learning outcomes. Half of the question items measured readers' retention knowledge, which assessed verbal recall after reading. The other half of the questions assessed readers' transfer knowledge, which assessed higher levels of understanding with regard to the learning materials.

Scoring

Standardized Measures

Standardized measures such as WISC, VPST-4, WCST-64, and WRMT-III were scored using the scoring procedures stated in each testing manual.

Computerized Color Stroop Task

Students' response time and accuracy for each stimulus were automatically recorded in ePrime software. The difference of total response time of accurate answers between congruent and incongruent conditions were calculated. Higher score indicates a better inhibitory control capacity.

Multiple-Choice Question Items in Learning Outcome Measure

Learning outcome measures included nine multiple-choice question items for each topic. Answer keys were created and used for scoring the multiple-choice question items. Participants received one point for a right answer. Thus, on each topic of reading material, students could earn a total score of nine for the multiple-choice items.

Open-Ended Questions

Rubrics (see Appendix C) were developed a priori to score students' responses for prior knowledge items and for the one open-ended question in the learning outcome measure. Answers for the open-ended questions were independently coded by the author and a graduate student who were trained in the field of elementary education and educational psychology. The inter-rater reliabilities were obtained by calculating the percentage of agreement for both prior knowledge measure (80.3%) and learning outcome measure (78.6%). Discrepancies were resolved through discussion.

Reading Materials

The topics of the eye tracking reading materials were *How Does a Steam Train Move?* and *How Does an Airplane Take Off?*[1] The topics were chosen to present content that is not familiar to the participants (i.e., fourth and fifth grade elementary students). The readability of

[1] The reading materials were adapted with permission from explainthatstuff.com.

each text was adjusted for fourth grade readers. Both unillustrated and illustrated conditions were developed for each topic of text. The unillustrated (i.e., text only) texts were composed of two parts: a title and a text segment. The illustrated (i.e., text with picture) texts were composed of three parts: title, a text segment, and a picture segment. The text segment was placed on the left side and the picture segment was on the right. For both topics, word count, the number of multisyllabic words, and readability were counterbalanced with one another and are shown in Table 5. Each text consisted of nine multiple-choice questions and one open ended question to assess learners' understanding of the text. These reading materials and learning outcome measures are shown in Appendix B. Children read both the illustrated and unillustrated texts. The order of the topic and illustrated condition were counterbalanced, and consequently, children read one of the four versions as shown in Table 6. The reading materials were presented on a computer monitor. I used a block randomization technique to randomly assign one of the four versions to the participants.

Table 5
Readability Profile of Both Topics of Reading Materials

	Steam Train	Airplane
Word count	153	153
Multisyllabic words	28	28
Number of sentences	11	11
Readability (Flesch-Kincaid)	4.2	4.0

Table 6
Versions of Reading Materials

Version	First text	Second text
A	Unillustrated Airplane	Illustrated Steam Train
B	Illustrated Airplane	Unillustrated Steam Train
C	Unillustrated Steam Train	Illustrated Airplane
D	Illustrated Steam Train	Unillustrated Airplane

Eye Tracking and Eye Movement Indices

While students read the texts, their eye movement patterns were recorded using an eye tracker. For eye tracking, participants were seated in front of a 22-inch widescreen monitor (resolution 1920x1080 [24 bits per pixel]; refresh rate 60Hz) with a viewing distance of approximately 80 centimeters between the monitor and the participant's eyes. To minimize head movement and standardize the viewing distance, participants were asked to use an adjustable chin rest and a forehead bar. Data were collected using SR Research EyeLink 1000 system (SR Research Ltd., Ontario, Canada) with a sampling rate of 1000 Hz from the right eye. The calibration and validation were deemed successful when an average error was less than 1° and a maximum error was less than 1.5°, as tested using a nine-point calibration. During the experiment, the calibration and validation were repeated after any breaks or whenever the experimenter considered it necessary. After successful calibration and validation, the reading materials were presented one by one. Children needed to solve comprehension question items after reading each topic. The question items were presented in a paper and pencil format.

In order to capture various aspects of reading processes, eye movement indices were adapted from previous text-picture integration studies (e.g., Johnson & Mayer, 2012; Mason, Tornatora, & Pluchino, 2013). The indices used in the present study are summarized in Table 7.

Table 7
Eye-Tracking Measures of Cognitive Processing During Learning

Name	Description	Cognitive Processes
Proportion of fixations on text	Number of fixations on picture divided by total number of fixations	Selecting: Attentional focus on words
Proportion of fixations on picture	Number of fixations on text divided by total number of fixations	Selecting: Attentional focus on pictorial elements
Integrative transitions	Total number of times the eye gaze is moved from text to picture and vice versa	Integrating: Attempts to integrate words and pictorial elements

Procedures

Data collection for this dissertation study was individually implemented in the neurobiological lab where the eye tracking research facility was already established. Children were accompanied by a parent to visit the lab, then parental consent and minor's assent were obtained in the beginning. After obtaining consent and assent forms, the parent was asked to stay in the waiting room and fill out two surveys containing demographic information and questions about their child's temperament. After a brief test of eyesight, the lab visit was roughly composed of three phases: the prior knowledge test, the eye tracking reading task, and cognitive and reading comprehension measures. Specific order, place, and materials used in the data collection are shown in Table 8. To minimize the effects of fatigue and boredom, children took short breaks between the phases or when they wished. Children also indicated, on their own volition, when they felt they were ready to begin a new phase. Participants received a 20-dollar gift card for completion of all sessions.

Table 8
Data Collection Procedure

Tasks	**Materials**
Greeting (consent/assent forms)	Consent/assent forms, pen
Demographic Survey	Survey questionnaire, pencil
Eyesight examination	Snellen chart, participant information sheet
Prior Knowledge Test	Prior knowledge test sheet, pencil, clip board
Eye Tracking (with comprehension test)	Learning outcome test sheet, clip board, pencil
Wisconsin Card Sorting Test	Test booklet, grading sheet
Digit Span Test	Test sheet
Test of Visual Perception Skill	Test booklet, grading sheet
Woodcock Reading Mastery Test	Test booklet, grading sheet
Color Stroop	Computer with ePrime software
Wrap-up	Gift card

Data Treatment and Analysis

Data were imported into SPSS (IBM Corp., 2012) version 21. Descriptive analyses were conducted to examine variability of each construct. Outlier analyses were implemented; outliers in the data were Winsorized to 2.5 standard deviation values (Tabachnick & Fidell, 2007). Histogram and boxplot were created to check assumptions, such as normality for multiple regression analyses. Correlation analyses were then implemented to examine preliminary associations among variables and multicollinearity issues among predictors.

To ensure equivalence of two reading topics, repeated measures ANOVA were conducted, comparing learning outcomes of two science topics. If there is no significant difference between the learning outcomes of two science topics, the reading materials and question items are equivalent. Additionally, to examine whether a multimedia effect exists, another repeated measures ANOVA was conducted to compare learning outcomes between illustrated and unillustrated conditions. If there is a significant difference between the learning outcomes of two conditions, we can conclude that there was a multimedia effect. In contrast, if there is no significant difference, we can conclude that adding pictures does not improve learning (i.e., no multimedia effect).

To answer research question one, which investigates the associations between integrative reading behaviors and learning outcomes, separate hierarchical regression analyses were conducted with learning outcomes as dependent variables and integrative transition as a predictor, while controlling for students' working memory and executive control capacities. Composite scores of each working memory and executive control were used due to the restriction of the number of independent variables in regression models.

To answer research question two, which examines the associations between students' working memory capacities and learning outcome, separate hierarchical regression analyses were conducted with both executive control and verbal/visuospatial working memory as predictors. For these analyses, learning outcomes were identified as the dependent variable while controlling for students' reading comprehension skills. The regression analyses were implemented for both illustrated and unillustrated conditions.

To answer research question three, which investigates the relations between students' working memory capacities and integrative reading, separate multiple regression analyses were conducted with verbal working memory, visuospatial working memory, and executive control as predictors. For these analyses, fixation count on text, fixation count on picture and integrative transition were identified as dependent variables.

CHAPTER IV

RESULTS

Introduction

This chapter presents the key results of the study. The purpose of this dissertation study was to examine the relationships among working memory, integrative reading behaviors, and learning outcomes while reading illustrated science texts. Participants were fourth and fifth grade elementary students who are fluent in English. Data were collected individually in a neurobiology lab. Research questions that guided this research were a) whether integrative reading behaviors are associated with learning outcomes, b) whether working memory capacities are associated with learning outcomes, and c) whether working memory capacities are associated with integrative reading behaviors. To present the results of the study, this chapter is organized into a) descriptive statistics, b) preliminary analyses, c) the association between integrative reading and learning outcome, d) the association between working memory and learning outcome, and e) the association between working memory and integrative reading.

Descriptive Statistics

Table 9 summarizes means, standard deviations, and skewness index for verbal working memory, visuospatial working memory, inhibitory control, attention shifting, passage comprehension score, prior knowledge, and post-test learning outcomes. Two composite scores were created and labeled "working memory" and "executive control." The working memory score was calculated by finding the sum scores for verbal working memory and visuospatial working memory. The executive control scores were calculated by combining the *z*-scores of attention shifting and inhibitory control. The skewness indices are considered acceptable when they are between -2 and +2 (Field, 2000; Field, 2009). Retention-based learning outcomes for unillustrated condition was negatively skewed. However, the value (-2.04) was marginally acceptable, thus, no further treatment was considered. Prior knowledge scores revealed most of the students did not have pre-existing knowledge on the topics of what they read, and therefore this was not examined further in the analyses.

Table 9
Descriptive Statistics of Variables

	Mean	SD	Skewness
Working Memory	40.86	5.63	0.05
Verbal Working Memory	13.43	3.02	0.52
Visuospatial Working Memory	27.43	3.41	-0.55
Executive Control			
Inhibitory Control	-34.89	41.68	-0.34
Attention Shifting	7.39	2.46	0.72
Passage Comprehension	14.36	4.84	-0.43
Posttest Learning Outcomes – Unillustrated	7.79	1.55	-0.32
Retention	4.54	0.88	-2.04
Transfer	3.21	1.23	0.21
Posttest Learning Outcomes – Illustrated	8.21	1.52	0.02
Retention	4.50	0.64	-0.92
Transfer	3.71	1.21	0.46
Integrative Transition	5.43	3.40	0.37
Fixation Count Percent			
Fixation Count on Title (%)	0.07	0.06	1.53
Fixation Count on Text (%)	0.90	0.07	-1.01
Fixation Count on Picture (%)	0.03	0.02	1.32

Correlations between variables are shown in Appendix D. Pearson Correlations were examined to identify a potential threat of multicollinearity. Variance Inflation Factor (VIF) values were also checked in the following regression analyses in order to further examine this issue. All VIF values were within acceptable range (i.e., - 3.0 ~ + 3.0), thus no multicollinearity was detected.

Preliminary Analyses

To ensure equivalence between the two reading materials on different topics (i.e., a steam train and an airplane), repeated measures ANOVA was conducted with the learning outcome of each topic. As shown in Table 10, the mean learning outcomes of the airplane text and the steam train text were 8.11 (SD = 1.52) and 7.64 (SD = 1.73), respectively. The result of the repeated measures ANOVA in Table 11 shows the learning outcomes based on the two different topics were not significantly different from one another (p = .182). This shows that the difficulty level of the materials and learning outcome measures was counterbalanced between the two reading materials.

Table 10
Descriptive Statistics of Reading Topics

Topic	Mean	SD	N
Airplane	8.11	1.52	28
Steam Train	7.64	1.73	28

Table 11
Within-Subjects Contrasts of Reading Topics

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Topic	3.018	1	3.018	1.874	.182
Error (Condition)	43.482	27	1.690		

Next, in order to examine whether learning outcomes were predicted by the presence of visual representation, another repeated measures ANOVA was conducted with regard to the learning outcomes of illustrated and unillustrated conditions. Table 12 shows the mean and standard deviation of the learning outcomes from illustrated and unillustrated conditions. The mean learning outcomes were 7.75 (SD = 1.56) and 8.00 (SD = 1.72), respectively, for each condition. The result of the repeated measures ANOVA in Table 13 shows that the learning outcomes of the two reading conditions were not significantly different from each other (*p* = .478), suggesting reading with visual representations did not produce a better learning outcome.

Table 12
Descriptive Statistics of Illustrated and Unillustrated Conditions

Condition	Mean	SD	N
Illustrated	7.75	1.56	28
Unillustrated	8.00	1.72	28

Table 13
Within-Subjects Contrasts of Illustrated and Unillustrated Conditions

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Condition	.875	1	.875	.518	.478
Error (Condition)	45.625	27	1.690		

Association Between Integrative Reading and Learning Outcome (RQ1)

Research question one investigated the unique, direct contribution of integrative transitions on students' learning outcome above the contributions of working memory capacities. Because integrative reading behavior of text and picture was examined in this question, only variables from illustrated texts were used in the analyses. The answer to the question was examined with separate hierarchical regression analyses, with independent variables of working memory, executive control, and integrative transition and the dependent variable was learning outcomes (i.e., total learning outcome, retention outcome, and transfer outcome). Due to the restriction of the number of variables in the regression models, composite scores were used for verbal working memory and visuospatial working memory, as well as executive control functions (i.e., attention shifting and inhibitory control).

Table 14 shows the results from the hierarchical regression analyses for the total learning outcome of the illustrated condition. The regression models tested whether integrative transition accounted for significant amounts of variance in the learning outcomes of illustrated text reading after controlling for working memory and executive control. Although Model 1 shows that working memory and executive control accounted for 35% significant variance in learning outcomes, Model 2 indicates that integrative transition did not account for significant variance of learning outcomes in the illustrated text condition.

Table 14
Hierarchical Regression Analyses for Learning Outcome

Model	t	p	b	β	R^2	ΔR^2	F
Model 1					0.35	0.35	6.76^{**}
Working Memory	3.01	0.006	0.13	0.49			
Executive Control	1.79	0.086	0.30	0.29			
Model 2					0.38	0.03	1.02
Working Memory	2.48	0.020	0.12	0.43			
Executive Control	2.01	0.056	0.35	0.34			
Integrative Transition	1.01	0.322	0.08	0.18			

Follow-up analyses were conducted with separate dependent variables of retention and transfer learning outcomes. As shown in Table 15, although Model 1 shows that working memory and executive control accounted for 35% of the variance, Model 2 revealed integrative transition did not account for significant variance in retention outcome. As shown in Table 16, for transfer outcome, integrative transition accounted for a significant 12 % of the variance, suggesting integrative transition has a unique, direct contribution on transfer learning outcomes over and above the contributions of working memory and executive control. Beta coefficient indicates that a one unit increase of integrative transition results in an increase of .13 points in transfer learning outcomes.

Table 15
Hierarchical Regression Analyses for Retention Learning Outcome

Model	*t*	*p*	*b*	*β*	R^2	ΔR^2	*F*
Model 1					0.35	0.35	6.76^{**}
Working Memory	1.99	0.058	0.04	0.32			
Executive Control	2.83	0.009	0.20	0.46			
Model 2					0.42	0.07	2.86
Working Memory	2.51	0.019	0.05	0.02			
Executive Control	2.31	0.030	0.16	0.38			
Integrative Transition	-1.69	0.104	-0.05	-0.29			

Table 16
Hierarchical Regression Analyses for Transfer Learning Outcome

Model	*t*	*p*	*b*	*β*	R^2	ΔR^2	*F*
Model 1					0.22	0.22	3.56^{*}
Working Memory	2.49	0.02	0.10	0.44			
Executive Control	0.69	0.50	0.10	0.12			
Model 2					0.34	0.12	4.29^{*}
Working Memory	1.79	0.09	0.07	0.32			
Executive Control	1.31	0.20	0.19	0.23			
Integrative Transition	2.07	0.05	0.13	0.38			

Association Between Working Memory and Learning Outcome (RQ2)

Research question two investigated whether components of executive control, such as attention shifting and inhibitory control, were related to the children's learning outcomes in either the illustrated or unillustrated text condition. This was examined with separate hierarchical regression analyses. For these analyses, the independent variables were reading comprehension, working memory, attention shifting, and inhibitory control, while the dependent variables were the learning outcomes from illustrated or unillustrated texts.

Table 17 shows the regression results for the unillustrated text condition. Both reading comprehension and working memory predicted learning outcomes of unillustrated text condition, whereas attention shifting and inhibitory control did not account for significant variance in the learning outcomes for unillustrated texts, as shown in Model 1. This pattern did not change when the order of attention shifting and inhibitory control was changed in Model 2.

Table 17
Hierarchical Regression Analyses for Unillustrated Text

Model	R^2	ΔR^2	F
Model 1			
1. Reading Comprehension	0.14	0.14	4.29*
2. Working Memory	0.28	0.13	4.61*
3. Attention Shifting	0.31	0.03	1.04
4. Inhibitory Control	0.36	0.06	2.08
Model 2			
3. Inhibitory Control	0.33	0.05	1.81
4. Attention Shifting	0.36	0.04	2.32

Table 18 summarized the regression results for illustrated text. For the learning outcomes in the illustrated text condition, Model 1 shows that reading comprehension and working memory accounted for 23% of the variance and attention shifting accounted for 17% of the variance, whereas the contribution of inhibitory control was not significant. The pattern did not change when the order of attention shifting and inhibitory control changed in Model 2, though the R square change value for attention shifting was reduced to 16%. The results suggest that in learning with visual representation, individual differences in attention shifting is associated with learning outcomes.

Table 18
Hierarchical Regression Analyses for Illustrated Text

Model	R^2	ΔR^2	F
Model 1			
1. Reading Comprehension	0.04	0.04	1.09
2. Working Memory	0.27	0.23	7.83^{**}
3. Attention Shifting	0.44	0.17	7.27^{*}
4. Inhibitory Control	0.48	0.04	1.62
Model 2			
3. Inhibitory Control	0.32	0.05	1.77
4. Attention Shifting	0.48	0.16	6.89^{*}

Association Between Working Memory and Reading Behaviors (RQ3)

Research question three investigated associations between working memory components and online reading behaviors as revealed by fixation count on text, fixation count on pictures, and integrative transitions between text and pictures. Multiple regression analyses were conducted, fixation counts and integrative transition being dependent variables and verbal working memory, visuospatial working memory and executive control as predictors. An enter approach was used to explore the relative contributions of verbal working memory, visual working memory, and executive control to either text processing, picture processing, or text-picture integrative processing. Regression results were summarized in Table 19.

Table 19
Results of Multiple Regression Analyses

Models	t	p	b	β	F	df	p	R^2
FC (text)					3.78	3, 24	0.024	0.32
VWM	-3.1	0.005	-0.01	-0.62				
VSWM	0.9	0.356	0.00	0.19				
EC	0.8	0.797	0.01	0.14				
FC (picture)					2.86	3, 24	0.058	0.26
VWM	1.8	0.088	0.00	0.37				
VSWM	1.0	0.341	0.00	0.20				
EC	0.3	0.762	0.00	0.06				
IT					1.68	3, 24	0.20	0.17
VWM	0.6	0.586	0.14	0.12				
VSWM	1.2	0.257	0.26	0.26				
EC	-1.5	0.137	-0.67	-0.29				

Note: FC = Fixation count; VWM = Verbal working memory; VSWM = Visuospatial working memory; EC = Executive control; IT = Integrative transition

The first model examined the association between working memory components and text processing by measuring the fixation count on text. The result revealed that 32% of the variance in fixation count on text were explained by working memory components. The second model examined the association between working memory components and picture processing as measured by fixation count on pictures. The result revealed that 26% of variance in fixation count on pictures were explained by working memory components. However, the F-statistics value was marginally significant ($p = .06$). The last model investigated the association between working memory components and integrative reading assessed by the integrative transition between text and picture. Children's integrative reading behavior was not significantly associated with working memory components.

Beta coefficients indicated that among the working memory components, verbal working memory was the only significant predictor of fixation count on text ($\beta = -0.62$, $p = 0.005$) and also marginally significant for fixation count on picture ($\beta = 0.37$, $p = 0.088$). The findings indicate that children with better working memory made less fixation on text and more fixation on pictures. However, visuospatial working memory and executive control were not significant predictors for any of the dependent variables.

CHAPTER V

CONCLUSIONS

Introduction

This study investigated the relationships between working memory components, integrative reading behaviors, and learning outcomes when fourth and fifth grade elementary students read illustrated science texts. Following Baddeley's component model of working memory, the roles of verbal working memory, visuospatial working memory, and executive control were also investigated. Executive control was further divided into attention shifting and inhibitory control. Children's integrative reading behaviors were recorded with an eye tracker. Fixation counts on either text or pictures were used for indicating text and picture processing, respectively. To indicate integrative reading of text and pictures, integrative transitions between text and picture were counted. During the lab visit, each child read both illustrated and unillustrated texts. Retention and transfer learning outcomes were measured with nine multiple choice question items and one open-ended question. Specifically, the present study investigated a) whether children's integrative reading behaviors make a unique, direct contribution on learning outcomes after accounting for working memory capacities, b) whether children's executive control makes a unique, direct contribution on learning outcomes when working with both unillustrated and illustrated texts, after accounting for the contributions of verbal and visuospatial working memory, and c) the relative importance of verbal working memory, visuospatial working memory, and executive control in either text processing, picture processing, and the integrative reading of text and pictures.

Multimedia Effect

As part of the preliminary analyses, the study investigated the effects of visualization on learning outcomes – namely, whether or not the presence of a picture produced a better learning outcome. Repeated measures ANOVA yielded no significant difference of learning outcomes between illustrated and unillustrated conditions. This finding indicates that there was no multimedia effect on whether or not a child was able to learn the scientific content. Even though no significant difference was observed between the two text conditions (i.e., illustrated and unillustrated), the mean score of learning outcomes in the unillustrated text condition was slightly higher than the mean score in learning outcomes in the illustrated text condition.

This result suggests that any visuals did not support the reading comprehension of learners. This finding appears to be somewhat surprising, given the strong belief in the effectiveness of visualization. It is expected that visual representation can provide supplementary information for learners to construct a more elaborate mental model (Mayer, 2014). In the learning materials used in this study, the airplane text included a visual representation depicting the physical appearance and shapes of airplane wings, as well as visual information about aerodynamics. In the steam train text, the visual representation illustrated the process by which steam is created, how steam moves through the boiler to the pistons, and how the movement of the pistons produce the movement of the wheels. However, the result of the ANOVA test shows that children did not make good use of the visual representation while they were reading. This result is consistent with findings that have been identified in literature concerning multimedia learning and science education: adding images does not improve learning (Bartholomé & Bromme, 2009). As shown in the literature review in chapter two, there are many text-related and learner-related factors that influence learning from multimedia texts. The preliminary analyses result sets the stage for the work being done by this dissertation study's investigations, especially with regard to working memory.

Association Between Integrative Reading and Learning Outcome (RQ1)

The first research question of this study was whether children's integrative reading behaviors are related to their learning outcomes. Hierarchical regression results revealed that children's integrative reading is associated with their learning outcome on transfer measure. Specifically, this study found that the more integrations children made, the better learning outcome they obtained on a transfer knowledge measure. In contrast, it should be noted that the association was not observed in the learning outcome of retention measure. This result suggests that integrative reading is more closely aligned with how children construct mental models, as well as a deeper understanding of the topics, not with surface knowledge.

This finding is partly consistent with Mason, Tornatora, and Pluchino (2013), which found the association between online cognitive processing and offline outcomes from an illustrated text. The authors found, from group comparisons (i.e., low, intermediate, and high integrators), that more strategic and integrative patterns of visual behaviors were associated with both retention and transfer knowledge. There are many differences between the current study and Mason, Tornatora, and Pluchino in terms of reading materials, study design, measures, and analytic approaches. Therefore, future research needs to further investigate this issue, especially with regard to whether integrative reading behaviors also contribute to retention knowledge.

This finding is especially significant given the prevalent adoption of visuals in textbooks. Without enough processing time and integrative reading behaviors, visual representations might not help learning, especially when considering transfer knowledge building. Accordingly, the results may suggest that classroom teachers need to explicitly teach and model how to integrate visual representations while reading illustrated scientific texts.

Association Between Working Memory and Learning Outcome (RQ2)

The second research question was whether children's working memory is associated with their learning outcomes. The relative contributions of attention shifting and inhibitory control as subcomponents of executive control were specified in learning from illustrated and unillustrated texts over and above the contribution of working memory. The results of hierarchical regression analyses revealed that while working memory accounted for the variance in learning outcomes in both unillustrated and illustrated texts, only attention shifting accounted for a significant variance in the learning outcomes from illustrated texts.

The significant relationship between verbal and visuospatial working memory and comprehension outcomes is consistent with findings from many other previous research studies shown in chapter two (e.g., De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005; Gyselinck, Meneghetti, De Beni, & Pazzaglia, 2009; Meneghetti, Gyselinck, Pazzaglia, & De Beni, 2009; Pazzaglia, 1999). Moreover, this finding is not surprising, given the role of processing capacity (i.e., working memory) in text processing skills when reading illustrated and unillustrated texts, such as a reader's ability to make inferences and monitor their own comprehension (Cain et al., 2004)

In the illustrated text comprehension, attention shifting is associated with learning outcomes. The finding suggests that when learners read illustrated science texts, it is important for them to flexibly allocate their attention to different pieces of textual and pictorial information most relevant to the learning goals (Baadte et al., 2015). The fact that attention shifting was not related with unillustrated text comprehension, is inconsistent with the previously identified relationship between attention shifting and reading comprehension skills. As Baadte et al. pointed out, however, the role of attention shifting is highly dependent on the cognitive demand of text materials. In the current study, cognitive demand of the illustrated and unillustrated text condition might have been a factor that determine the involvement of attention shifting.

The non-significant relationship between inhibitory control and learning outcomes is somewhat unexpected and is not consistent with previous literature, which found that inhibitory control plays a significant role in reading comprehension (Baadte et al., 2015). It was expected that learning with visualization requires learners to perform effortful suppression of irrelevant information, as visual representations tend to more include more irrelevant elements than textual representation. One possible explanation of this unexpected finding is that inhibitory control may have multiple subcomponents. For example, Arrington, Kulesz, Francis, Fletcher, and Barnes (2014) found that cognitive inhibition, rather than behavioral inhibition as measured in this dissertation study, was associated with reading comprehension skills. One important difference between Arrington et al. and the current study is that the present study examined the relationship between inhibitory control and learning outcomes, not general reading comprehension skills. Therefore, future research needs to further investigate the relationships of both cognitive and behavioral inhibition to actual learning outcomes.

Association Between Working Memory and Reading Behaviors (RQ3)

The third research question was concerned with the relative contributions of different working memory components when reading illustrated texts. The effects of verbal working memory, visuospatial working memory, and executive control on either text processing, picture processing, and integrative processing were examined using separate multiple regressions. Based on previous research findings, it was expected that verbal working memory was to be associated with text processing, visuospatial working memory with picture processing, and executive control with integrative processing of text and picture. However, the multiple regression analyses revealed the predictors produced an explanation for the variance in text processing measured by fixation count on text, as well as a marginal explanation for the variance in picture processing measured by fixation count on pictures. However, integrative reading behavior was not associated with any of the working memory components.

Limitations of the Study

This study has several limitations. First and foremost, this study was conducted in a research lab setting where tasks were completed individually. While reading the text materials, students needed to use a chin rest and forehead bar to minimize their movements. This unnatural circumstance might have affected the reading behaviors of the participants. Thus, the findings of the study might not be able to be generalized to an actual classroom setting or when a child is engaged in uninterrupted reading. Future research can be conducted in an actual classroom setting with a portable eye tracker. Another limitation to the study was the small sample size. Due to this factor, to the number of predictors in a model had to be restricted to less than four by using composite scores (e.g., composite scores for verbal and visuospatial working memory; composite scores of attention shifting and inhibitory control). With a larger sample, the future studies can further examine the role of each specific construct with more statistical power. Third, only two texts with limited text-related factors were used in this study. Associations in this study might vary, depending on the other text-related factors included, but were not limited to, signals, spatial contiguity, the degree of information overlap, text difficulty, and picture characteristics. Therefore, future research needs to examine the associations between readers' cognitive capacities, integrative reading behaviors, and learning outcomes with various text-related factors.

Finally, for the integrative reading behaviors, this study only used eye movement measures. Although eye tracking provides accurate and extensive information about children's online reading behaviors, the use of other traditional measures, such as a think-aloud or post-reading interviews for integrative reading behaviors will corroborate the validity of students' text-picture integration and triangulate the findings of the study.

Significance of the Study

This study adds to existing literature focused on the relationship among working memory, integrative reading behaviors, and learning outcomes when upper elementary students read scientific texts. This study contributes to the limited body of knowledge regarding the role of executive control in upper elementary students' learning with illustrated text and their integrative reading behaviors. Further, with the findings regarding the role of executive control, this study supplements the current Cognitive Theory of Multimedia Learning. Finally, this study gives practical implications on the development of visual literacy interventions, as well as on how teachers can design their instruction.

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APPENDIX A

LITERATURE REVIEW

Title	Research topic	Research questions and Hypotheses	Populations Design	Measures	Results	Missing parts
Bartholomé, T., & Bromme, R. (2009). Coherence formation when learning from text and pictures: What kind of support for whom?. *Journal of Educational Psychology*, *101*(2), 282.	The effects of mapping support and prompting in coherence formation	1. The combination of prompts and highlighting will produce the best learning outcomes. 2. Spatial abilities and verbal working memory span will be potential moderators of the effectiveness of the different help facilities.	College Students (N=84, age=24.7), laypeople in botany * Mapping support (label vs. highlight), prompting (given vs. not given)	Spatial ability (mental rotation), working memory (digit span), confidence rating (5-point scale), posttest (verbal retention, verbal understanding, visual understanding, classification, and global understanding)	1. The best learning results are achieved when minimal support is given, such as in the condition with numerical labels and no prompts. 2. Spatial ability moderate the effectiveness of prompting. 3. working memory span had not moderating effect.	Reading processes data (e.g., eye movement) were not collected.
Johnson, C. I., & Mayer, R. E. (2012). An eye movement analysis of the spatial contiguity effect in multimedia learning. Journal of *Experimental Psychology: Applied, 18*(2), 178.	Spatial contiguity	1. Learners in the integrated condition would make more integrative transitions and corresponding transitions. 2. Learners in the integrated group would perform better than those in the separated group on a transfer test.	College Students (N=44, age=19.02) integrated condition vs. separated condition	Spatial ability (card rotations, paper folding), retention test (1 item), transfer test (5 items)	1. Integrated group made more integrative transition and corresponding transitions 2. Integrated group had significantly higher scores on the transfer test.	Spatial ability was not examined as a significant factor for predicting coherence formation. It was only used to control individual differences. Working memory data were not collected.
	Spatial contiguity	1. Learners in the integrated with label condition would make more integrative transitions and corresponding transitions. 2. Learners in the integrated group would perform better than those in the separated group on a transfer test.	College Students (N=58, age=18.69) integrated with label vs. separated	Spatial ability (card rotations, paper folding), retention test (1 item), transfer test (5 items)	1. Integrated with labels group made significantly more integrative transitions than the separated group. 2. Integrated with labels group had significantly higher scores on the transfer test.	
	Spatial contiguity	1. Learners in the integrated condition would make more integrative transitions and corresponding transitions. 2. Learners in the integrated group would perform better than those in the separated group on a transfer test.	College Students (N=50, age=18.88) integrated condition vs. legend condition	Spatial ability (card rotations, paper folding), retention test (1 item), transfer test (5 items)	1. Integrated group made more corresponding transitions than the legend group. 2. Performance on transfer tests was not significantly different between groups.	

Mason, L., Pluchino, P., & Tornatora, M. C. (2013). Effects of picture labeling on science text processing and learning: Evidence from eye movements. *Reading Research Quarterly, 48*(2), 199-214.	Effects of picture labeling	1. Is reading a text with picture is more effective than nonillustrated text? 2. Labeled picture induce different cognitive processing (i.e., eye movement)? 3. Are there relations between eye movement patterns and learning outcomes?	6th grade student's (N=56, age=11.10) Text-only vs. text with unlabeled illustration vs. text with labeled illustration	Posttest (factual, transfer), reading comprehension, verbal working memory (reading span), visuospatial working memory (corsi span), spatial ability (mental rotation), achievement in science	1. No significant effect for factual knowledge, significant effect of labeled picture condition for transfer. 2. Label can improve the efficacy of the mapping process. 3. There are some links between online integration and learning performance.	Interaction between individual differences (i.e., reading comprehension, WM, spatial ability) and group was not examined.
Jian, Y. C. (2016). Fourth graders' cognitive processes and learning strategies for reading illustrated biology texts: eye movement measurements. *Reading Research Quarterly, 51*(1), 93-109.	Eye movement patterns in illustrated reading	1. Young readers are less capable of using illustrated information? 2. University students will show bidirectional reading path?	4th grade students and College Students (N=14, 15, age=10.4, 21.05) (4th grade students vs. college students)	Posttest (7 recognition, 3 textual, and 7 illustration items)	1. University readers emphasized the role of illustration more than the fourth-grade students did. 2. University readers showed bidirectional reading pathways, but fourth grade studnts' demonstrated unidirectional reading pathways.	Individual differences were not examined. Relationship between eye movement patterns and learning outcomes was not examined.
Scheiter, K., & Eitel, A. (2015). Signals foster multimedia learning by supporting integration of highlighted text and diagram elements. *Learning and Instruction, 36*, 11-26.	Signaling effect	1. Signal group will have better learning gains. 2. (Specific signaling effect) Signal group will attend to signaled elements more frequently, and faster than nonsignal group and will show more transition. These will mediate learning outcomes.	College Students (N=53, age=24.11) signal group vs. nonsignal group	Posttest (verbal recall, transfer, integration), prior knowledge test (5 items)	1. Signal group scored higher on integration questions. 2. Learners in the signaling condition attended more frequently and earlier to the signaled elements. However, no evidence for more transition for the signal group.	No individual differences data were collected or examined.
	Whether signaling effect is specific or general	3. (Specific signaling effect) Mismatched signal group will yield more frequent and faster attention to signaled elements as well as higher number transition. But these will not mediate learning outcomes. 4. (General signaling effect) Two signaling groups will attend to signaled and nonsignaled elements more frequently. These will mediate learning outcomes.	College Students (N=43, age=21.80) signal group vs. mismatched signal group	Posttest (verbal recall, transfer, integration), prior knowledge test (5 items)	3. Mismatched signals yielded more frequent and earlier attention to signaled elements, but mismatched signals did not lead to better learning outcomes. 4. Both hypotheses were not supported.	

McNamara, D. S. (2001). Reading both high-coherence and low-coherence texts: Effects of text sequence and prior knowledge. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *55*(1), 51.	The source of the comprehension advantage produced by low-coherence text for high-knowledge readers.	1. Whether the advantage for the low-coherence text is due to inferences that are generated during encoding, or inferences during testing 2. Whether the inferences must rely on prior knowledge, or whether inferences based on the text are sufficient. 3. Potential advantage of reading two text versions that differ in coherence.	College Students (N=80) * Between: first text (high cohesion vs. low cohesion), same-different (same text vs different text), prior knowledge (high vs. low) * Within: question type (text-based vs. situation model)	Text-based questions (11 items), situation model questions (11 items), prior knowledge questions (14 items)	1. High-knowledge readers will learn more from a low-coherence text because they are more likely to generate knowledge-based inferences while reading the text. 2. The best comprehension emerged for high-knowledge readers in the low/high condition. 3. Low knowledge participants benefit more from reading different texts.	Science texts usually accompany with visuals. The visual display influences readers' reading patterns and comprehension. Therefore, research on science text comprehension should address visual display as an important factor.
Ozuru, Y., Dempsey, K., & McNamara, D. S. (2009). Prior knowledge, reading skill, and text cohesion in the comprehension of science texts. *Learning and instruction*, *19*(3), 228-242.	Prior knowledge, reading skill, and text cohesion in the comprehension of science texts	Q1. How does the relative contribution of prior knowledge and reading skill to comprehension change as a function of type of comprehension questions? Q2. What is the relative contribution of prior knowledge and reading skill to the benefit and/or detrimental effect of text cohesion on comprehension? H1. Prior knowledge has a greater contribution to comprehension of science text than reading skill. H2. Contribution of prior knowledge would be larger for local- and global-bridging questions. H3. Low-knowledge participants will benefit more from the high-cohesion text. H4. High-knowledge participants will shallowly process the high-cohesion text. H5. The benefit of a high-cohesion text will be limited to lower levels of comprehension.	College Students (N=108 from UM, age=21.1, N=62 from ODU biology course, age=23.3) * Within-subject: text cohesion (low and high), questions type (text-based, local-bridging, and global bridging) * Between-subject: prior knowledge (low vs. high)	* 12 comprehension questions for each text (4 text-based, 4 local-bridging, 4 global-bridging) * reading skill (Nelson-Denny), biology knowledge (21 multiple choice), topic-specific knowledge (16 open-ended)	1. Beta weights of biology knowledge and topic-specific knowledge were larger than the beta weight of reading skill (H1). 2. When questions demanded more extensive information integration, the contribution of prior knowledge increase and the contribution of reading skills decrease (H2). 3. The benefit of text cohesion was limited to performance on text-based questions (H5). 4. High-knowledge less-skilled readers performed more poorly when reading a high-cohesion text than when reading a low-cohesion text (H4). 5. Benefit of text cohesion depends on reading skill.	Science texts usually accompany with visuals. The visual display influences readers' reading patterns and comprehension. Therefore, research on science text comprehension should address visual display as an important factor.

O'reilly, T., & McNamara, D. S. (2007). Reversing the reverse cohesion effect: Good texts can be better for strategic, high-knowledge readers. *Discourse processes*, *43*(2), 121-152.	Reverse cohesion effect + reading skill	Q1. Only less skilled, high-knowledge readers would comprehend more from the low-cohesion text, whereas skilled, high-knowledge readers would not display a reverse cohesion effect.	College Students (N=143, age=22.59) * Within-subject: question type (text-based or bridging) * Between-subject: text type (high cohesion or low cohesion), science knowledge (high, low)	Prior knowledge tests (multiple choice, open-ended), Comprehension skill (Nelson-Denny, MSI), Comprehension questions (10 open ended, 5 text-based, 5 bridging-inference)	1. skilled, high-knowledge readers performed better on the high-cohesion text. 2. reverse cohesion effect occurs only for less skilled, high-knowledge readers. 3. Cohesion helps low-knowledge readers on bridging-inference questions. 4. Active processing helps low-knowledge readers.	No multimedia text
Roscoe, R. D., Jacovina, M. E., Harry, D., Russell, D. G., & McNamara, D. S. (2015). Partial verbal redundancy in multimedia presentations for writing strategy instruction. *Applied Cognitive Psychology*, *29*(5), 669-679.	Partial redundancy principle in a writing strategies tutoring system	1. Do adolescent students improve their knowledge of writing by studying animated lessons provided by W-Pal? 2. Are knowledge gains influenced by the degree of redundancy? 3. Are knowledge gains influenced by prior reading ability? 4. How do degrees of redundancy and prior reading ability interact to influence learning?	High school students (N=90, Grade=9-12) * Within-subject: instruction (pretest vs. posttest * Between-subject: degree of redundancy (50%, 26%, 10%) * Covariate: prior reading ability		1. Students increased significantly in their knowledge of cohesion from pretest to posttest. 2. The degree of partial redundancy do not significantly influence learning gains. 3. More-skilled readers possessed significantly more knowledge about cohesion than less-skilled readers. 4. There was no interaction between reading skill and learning with partially redundant presentations.	The study focused on modality effect (text and audio) in multimedia presentation. Text-picture integration was not examined.

Mason, L., Tornatora, M. C., & Pluchino, P. (2013). Do fourth graders integrate text and picture in processing and learning from an illustrated science text? Evidence from eye-movement patterns. *Computers & Education*, *60*(1), 95-109.	Text-picture integration in 4th grade students	1. Are different patterns of readers' eye movements during the first- and second-pass reading identifiable during the learning episode? 2. Are readers' eye movements related to their individual characteristics of prior knowledge, reading comprehension ability, and spatial ability? 3. Is readers' learning from illustrated science text related to their patterns of eye movements during text reading and picture inspection, after controlling for individual differences?	4th grade students (N=49, age=9.7)	* Posttest (free recall, 5 open-ended factual, five open-ended transfer) * Reading comprehension (14 multiple-choice) * prior knowledge (5 open ended) * spatial ability (Primary mental ability test)	1. Integrative processing differentiates across three eye movement patterns (intermediate integrators, low integrators, high integrators). 2. Prior knowledge correlated positively with the number of integrative transitions and the look-from text to picture fixation time. Reading comprehension ability correlated negatively with the first-pass fixation time on the text. Spatial ability did not correlate with any eye-movement index. 3. Learning outcomes were associated with the patterns of visual behavior.	Associations between individual characteristics (reading comprehension skill, prior knowledge, and spatial ability) were examined with correlation analysis. No association was found for spatial ability and integrative eye movement. Limitation: more rigorous stat analyses needed, text type needs to be considered (e.g., text requiring spatial processing)
Schmidt-Weigand, F., & Scheiter, K. (2011). The role of spatial descriptions in learning from multimedia. *Computers in Human Behavior*, *27*(1), 22-28.	Spatial text reading in multimedia environment	1. A stronger multimedia effect for high spatial text than low spatial text. 2. (alternative hypothesis) A stronger multimedia effect for low spatial text.	College Students (N=73, age=22.18) * Between: Degree of spatial information (high vs. low), presentation format (text-only vs. text + animation)	* prior knowledge (7 multiple choice) * cognitive load questionnaire (4 likert scale) * retention & transfer test * visual test (five items)	Internal representation of visuo-spatial information was affected by the degree of spatial information in the text.	Reading processes were not examined. Text + animation examined. Individual characteristics were not measured.

APPENDIX B

READING MATERIALS AND COMPREHENSION TEST ITEMS

Directions

Read the following text carefully.

How Does an Airplane Take Off?

Do you know how a big, heavy airplane can fly? When a plane moves into the wind, the wings cut the air in half. Some air goes over the wing. Some air goes under the wing. Plane wings are built to be curved on top, and flat on the bottom. The wind going over the wing travels a different path from the wind going under the wing. The different paths of the wind make lower air pressure over the wing, and higher air pressure under the wing. As the plane goes fast down the runway, the high air pressure under the wing lifts the plane into the air making lift. When there is strong lift, the plane takes off. All the time, the plane is being slowed down since it has to push through the air. As long as the plane keep moving forward at a fast speed, the plane continues to fly.

Read each question carefully. <u>Circle</u> the best answer for each question. Please <u>do not</u> go back to the text.

1. Which of the following is true about airplanes?

   A Airplanes take off because gravity lifts them.

   B Airplanes take off because they are not heavy.

   C Airplanes take off because their engines lift them.

   D Airplanes take off because high air pressure lifts them.

2. When a plane moves into the wind, the wings cut ____ in half.

   A the air

   B the wings

   C the plane

   D the runway

3. What is <u>not</u> necessary for an airplane to take off?

   A Air

   B Lift

   C Wings

   D Slow Speed

4. Plane wings are built to be ______.

A flat on both top and the bottom

B curved on both top and the bottom

C curved on top and flat on the bottom

D curved on the bottom and flat on top

5. What will most likely happen when the wings are built to be flat on top?

A Nothing happens

B The plane cannot run fast.

C The wings cannot make lift.

D The wings cannot cut the air in half.

6. During the flight, a plane is being slowed down because _____.

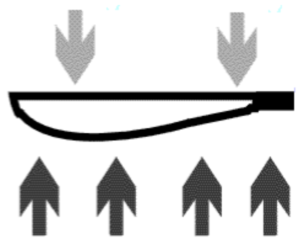
A it continues to fly

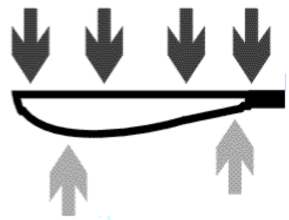
B its wings cut the air in half

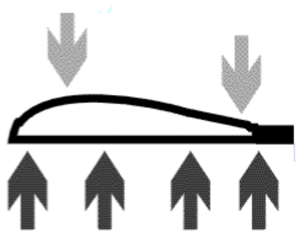
C the wings is curved on top

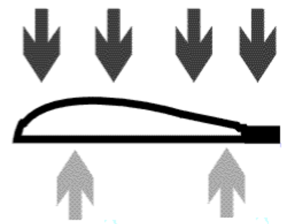
D it has to push through the air

7. Which of the following correctly illustrates the shape of the wing and the air pressure?

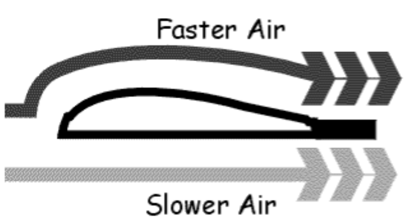
A 

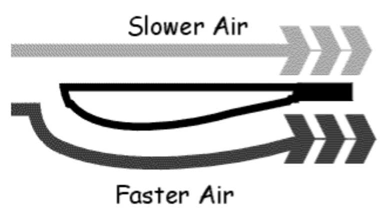
B 

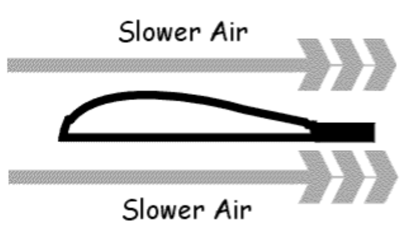
C 

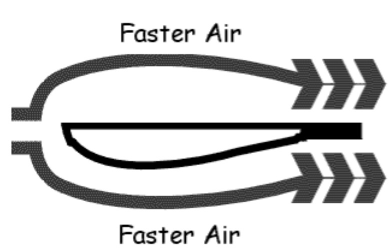
D 

8. Which of the following correctly illustrates the shape of the wing and the paths of the wind?

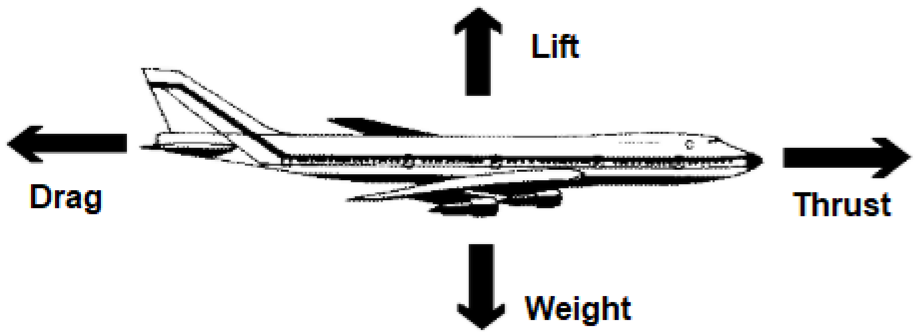
A 

B 

C 

D 

9. The picture below illustrates four forces on an airplane.



Which of the following correctly describes the magnitude of forces when a plane takes off?

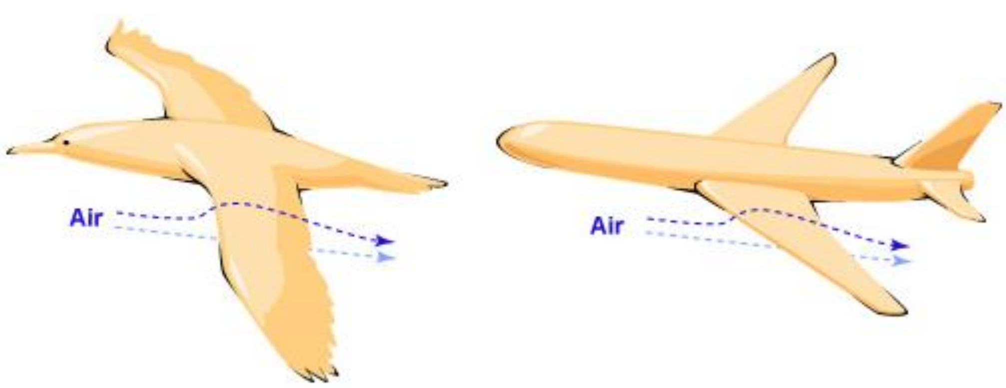
A Lift > Drag

B Lift > Weight

C Drag > Thrust

D Thrust > Weight

10. When airplanes take off, engines are needed to create lift. Then, how can birds create lift without engine?



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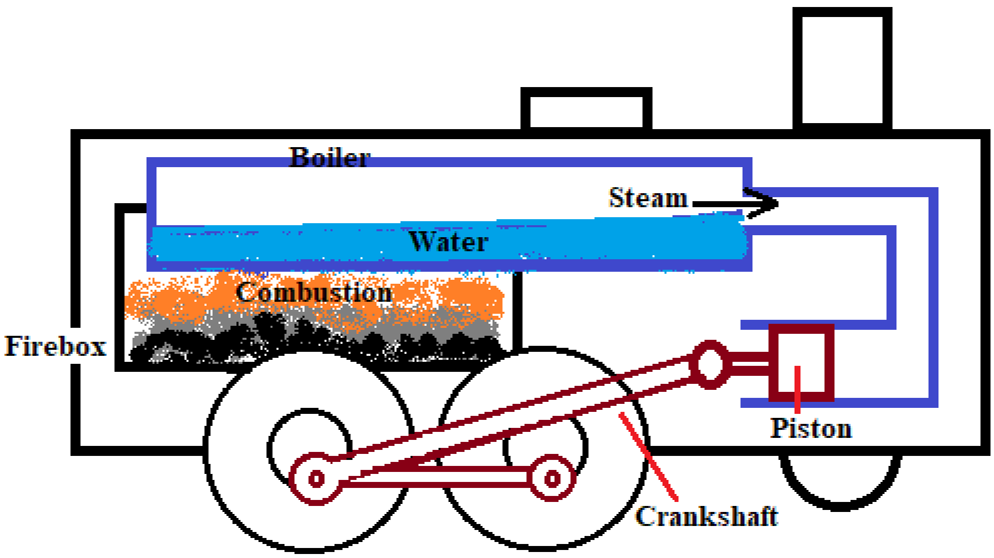
Directions

Read the following text carefully.

How Does a Steam Train Work?



Steam trains are powered by stream engines. There are four parts in a steam engine: a firebox, a boiler, a piston, and wheels. In the firebox, coal is used to heat up a big tank of water called a boiler. As the water heats up, it turns into steam. If you have ever seen a pot of boiling water, you may know how much steam it can create. In fact, if you put a lid on the pot, it will whistle like a tea kettle. The steam is squeezed into a very small space and forced into a metal rod. Then, the steam is pushing so powerfully that it moves the piston back and forth. The piston is linked to the wheels of the train. The wheels start moving, and the pistons keep pumping! If the pistons start to lose power, more coal can be added to the fire to create more steam.

Directions

Read each question carefully. <u>Circle</u> the best answer for each question. Please <u>do not</u> go back to the text.

1. Which of the following is true about steam trains?

    A Steam makes the steam engine stop.

    B To move, steam trains need electricity.

    C Sunlight makes steam trains move faster.

    D When pistons pump, the wheels start moving.

2. Stream trains use ____ to boil water.

    A coal

    B steam

    C a piston

    D a metal rod

3. What is <u>not</u> necessary to move pistons in a steam train?

    A Fire

    B Coal

    C Water

    D A Kettle

4. Steam is made when _____.

A water is boiling

B a train is moving

C a piston is pumping

D wheels start moving

5. What will most likely happen when the coal ran out?

A Nothing happens.

B More steam will be created.

C The pistons will stop moving.

D The wheels are moving faster.

6. To make the steam train faster, we can _______.

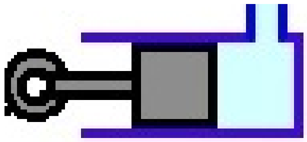
A add more coal

B add more water

C use bigger wheels

D use bigger pistons

7. Please choose the correct label for the picture below.



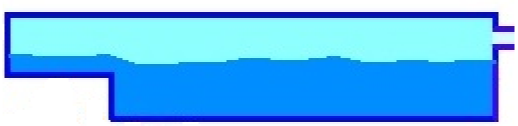
A Boiler

B Piston

C Crankshaft

D Steam Engine

8. Please choose the correct label for the picture below.



A Boiler

B Piston

C Crankshaft

D Steam Engine

9. Which of the following shows energy conversion in a steam train?

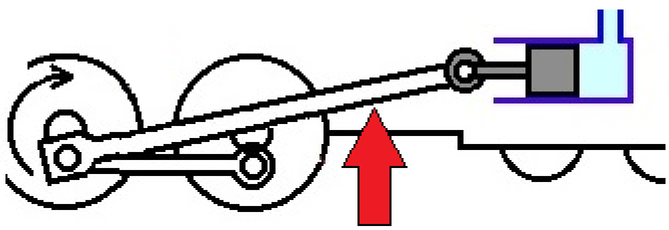
A Chemical energy → Heat energy → Kinetic energy

B Heat energy → Kinetic energy → Chemical energy

C Chemical energy → Heat energy → Potential energy

D Chemical energy → Potential energy → Kinetic energy

10. What is the role of the part indicated on the picture below?



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APPENDIX C

SCORING RUBRIC FOR OPEN-ENDED QUESTIONS

	Question	Scoring Approach	Example	Point
Prior Knowledge (Steam Train)	Do you know how a steam train moves?	The principle of steam train is not presented.	Neither 1 nor 2 is mentioned. Or not answered.	0
		The principle of steam train is partially presented.	Either 1 or 2 is mentioned.	1
		The principle of steam train is fully presented.	1. Steam is created by burning coal. 2. Steam push the piston and the piston move the wheels.	2
	Do you know what is necessary for a steam train to move?	No element is mentioned.		0
		One element is mentioned.		1
		Two to three elements are mentioned.	Coal (heat), steam (water), piston	2
Prior Knowledge (Airplane)	Do you know how an airplane takes off?	The principle of airplane take-off is not presented.	Neither 1 nor 2 is mentioned. Or not answered.	0
		The principle of airplane take-off is partially presented.	Either 1 or 2 is mentioned.	1
		The principle of airplane take-off is fully presented.	1. The wings cut the air in half when it runs fast. 2. Air pressure difference is created to lift the airplane.	2
	Do you know what is necessary for an airplane to take off?	No element is mentioned.		0
		One element is mentioned.		1
		Two to three elements are mentioned.	Wings, fast speed, engine	2
Posttest (Steam train)	What is the role of the part indicated on the picture below?	Not mentioned.	Neither 1 nor 2 is mentioned. Or not answered.	0
		One of the roles of crankshaft is mentioned.	Either 1 or 2 is mentioned.	1
		Two roles of crankshaft are mentioned.	1. It connects piston and wheels. 2. It changes back-and-forth motion into rotational motion.	2
Posttest (Airplane)	When an airplane takes off, engines are needed to create lift. Then, how can a bird create lift without engine?	Not mentioned.	Incorrect answers.	0
		The way a bird create lift is partially explained.	They use wings to lift.	1
		The way a bird create lift is fully explained.	A bird flaps their wings to create air pressure differences between above and under the wings.	2

APPENDIX D

CORRELATION TABLE

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Age	1																
2	WM	.03	1															
3	VWM	.02	-	1														
4	VSWM	.04	-	.53**	1													
5	EC	-.16	.11	.01	.17	1												
6	IC	.02	.02	-.07	.09	.73**	1											
7	AS	.24	-.34	-.26	-.33	-.70**	-.13	1										
8	PC	.25	.33	.25	.31	-.26	-.15	.20	1									
9	PT_Un	.05	.47*	.39*	.42*	-.07	.19	.07	.38*	1								
10	PT_Un_R	0	.40*	.24	.44*	.18	.39*	-.08	.14	-	1							
11	PT_Un_T	.03	.14	.16	.08	-.25	-.02	.23	.35	-	.06	1						
12	PT_Ill	-.07	.52**	.38*	.52**	.34	.23	-.53**	.20	.52**	.35	.31	1					
13	PT_Ill_R	.12	.37	.21	.43*	.49**	.40*	-.44*	.20	.37*	.30	.19	-	1				
14	PT_Ill_T	-.20	.46*	.37	.42*	.17	.07	-.43*	.14	.46*	.29	.29	-	.29	1			
15	IT	-.10	.30	.26	.27	-.25	-.03	.26	.33	.37	.18	.32	.22	-.26	.42*	1		
16	FC_Title	-.07	.18	.36	-.03	-.21	-.11	.16	.35	.25	.21	.15	.09	-.24	.24	.49**	1	
17	FC_Text	.03	-.35	-.52**	-.11	.16	.14	-.06	-.36	-.26	-.19	-.12	-.11	.21	-.25	-.48**	-.93**	1
18	FC_Pic	.11	.50**	.48*	.41*	.09	-.08	-.22	.12	.15	.01	.01	.14	.12	.11	.12	-.06	-.29

Note: WM = Working Memory; VWM = Verbal Working Memory; VSWM = Visuospatial Working Memory; EC = Executive Control; IC = Inhibitory Control; AS = Attention Shifting; PC = Passage Comprehension; PT_Un = Posttest of Unillustrated condition (R: retention, T: transfer); PT_Ill = Posttest of Illustrated condition (R: retention, T: Transfer); IT = Integrative Transition; FC = Fixation Count